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Industrial *Cannabis sativa* (Fiber or Hemp): Hemp Cottonization-Advantages and Current Challenges

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Abstract

Industrial *Cannabis sativa* (hemp or fiber type) has many applications particularly to produce paper, ropes, food, medicines, cosmetics, hempcrete, leather, bioplastic, biochar, 3D printing and textiles. Hemp fibers are used to create durable and eco-friendly fabrics for clothing, upholstery, and accessories. Hemp clothing is valued for its durability, breathability, and biodegradability, making it a preferred choice for conscious consumers. Hemp has been the mostly blended with cotton and synthetic fibers due to barriers in the industrial process of the production of full hemp-based textiles. India is the second-largest textile producer in the world. Digital, 3D Printing and 3D textile printing are emerging as game-changers in the Indian textile industry. Textile designers in India are already using 3D printing to create intricate patterns and textures on fabric, offering consumers a unique, personalized experience. One such major challenge is non-compatibility of hemp with modern textile machinery. The best way to process hemp is 'cottonization' of hemp. Cottonization is defined as the process of converting the hard bark of a hemp plant into a cotton like structure so that it can be used on dry spinning systems. Methods of hemp fiber extraction include dew retting, water retting, osmotic degumming, enzymatic retting, steam explosion and mechanical decortication to decompose pectin, lignin and hemicellulose to remove them from the stem with varying efficiency. However, there are several challenges associated with hemp processing as the fiber is coarse, stiff and it has comparatively poor spinnability particularly when 100% hemp is processed in ring spinning system. India has the potential to lead the global hemp revolution, there are challenges to overcome. The Indian hemp clothing market faces challenges related to regulatory issues, public perception, and sourcing of hemp fibers. However, as more research highlights the environmental and economic benefits of hemp, the stigma is gradually fading. The lack of production of specialized industrial machines dedicated to hemp fibers results in the high diversity of technological lines used and makes it impossible to evaluate the universal economic aspects of hemp yarn manufacturing.

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Keywords: Cottanization; Bast Fibres; Hemp Fabric; India; Textile; 3D Printing; Retting**.**

1. Introduction

Cannabis sativa L. belongs to the family *Cannabaceae* was used as a medicine before the Christian era in Asia, mainly in India, China, Bhutan, Nepal, Afghanistan, Pakistan, Egypt, Africa, Iran, Persians and Latin America [1-40, 148]. Hemp and India have a long drawn history. It is not a simple history by any means, it starts with history but extends itself through mythology, religion, cultures, traditions and life [1-40, 141, 153-173]. It has had a profound influence on agricultural, economic, and cultural developments in many regions around the globe [1-40, 148, 149]. The unique properties of cannabis have been utilized for medical, recreational, spiritual, and industrial purposes. While some cultures and governments have celebrated cannabis, others have feared, regulated, or outlawed its possession and determined it to be an illicit drug [149]. At present, *Cannabis sativa* is domesticated and cultivated in many countries, like USA, Canada, Australia, and many European countries, South Africa, and Latin America where it is used as a herbal drug particularly THC and CBD for controlling many human diseases [1-40, 148]. There are more than 750 hybrid varieties of *Cannabis sativa* are available in market [1-40, 153, 166]. Cannabis has been used for thousands of years for recreational, medicinal, or religious purposes [1-40]. Cannabis is also a wild noxious weed with notorious psychoactive principle (THC) found growing in all the parts of India [1-40]. Cannabis has a long history in India, recorded in legends and religion [1-40]. It was found in various habitats ranging from sea level to the temperate and alpine foothills of the Indian Himalaya Region from where it was probably spread over the last 10,000 years [1-40]. Many historians believed that Indian Himalayan Region was the centre of origin of *Cannabis sativa* L. and *Cannabis indica* [1-40-174].

Cannabis sativa L. is a wind-pollinated, dioecious medicinal plant (i.e., the male and female reproductive structures are on separate plants), although monoecious plants (male and female flowers on same plant) can occur in some population [1-40]. Male plants die shortly after flowering [1-40]. The female plants live 3 to 5 weeks until seed is fully riped [1-40]. Therefore, the plants are obligatory out-crossers [1-40]. In commercial production, Medical *Cannabis sativa* (drug or marijuana type) plants are all genetically female and male plants are destroyed as seed formation reduces flower quality [1-40]. Monoecious individuals are found with hermaphrodite flower or bisexual inflorescence [1-40, 168-174].

Cannabis sativa L., is classified into two types as Industrial *Cannabis sativa* (fiber or hemp) and Medical *Cannabis sativa* L.(drug or marijuana) based on its Λ9-tetrahydrocannabinol (THC), content [1-40]. Medical *Cannabis sativa* (drug or marijuana) contains very high levels of Λ9-tetrahydrocannabinol (THC) (above 0.3 to 38% of dry weight) and grown inside the greenhouse controlled conditions for the production of unfertilized female flowers [1-41]. These female flowers accumulates the psychoactive molecule THC and used for treatment of many health disorders [1-41, 166]. On the other hand Industrial *Cannabis sativa* L. (fiber or Hemp) contains very low levels of THC (0 to 0.3% of dry weight) grown outside in a large agriculture farms for the production of fibre, seeds and oil [1-40]. Hemp is used as a functional food and medicine since it contains Cannabidol (CBD), and very low levels of THC [1-40]. Therefore, Industrial *Cannabis sativa* L. (fiber or Hemp) type is genetically modified variety with very low levels of Λ9-tetrahydrocannabinol (THC) (0 to 0.3 %) [1-40, 166]. In this context, it is important to separate industrial hemp (fiber and food) and the narcotic variation of the Cannabis genus [1-40, 41, 148, 174]. Industrial hemp and marijuana share the same species, *Cannabis sativa* L, but represent different varieties [1-41]. As such, there are genetic differences that lead to different chemical characteristics, which, in turn, lead to different uses [41-51]. Moreover, the cultivation of Industrial *Cannabis sativa* L. (fiber or Hemp) type was prohibited in several countries due to the association with the production of illegal substances [1-41]. Historical misconceptions have resulted in lingering regulations and prejudices, hindering hemp cultivation and limiting the textile industry's access to valuable feedstock [29, 41]. To pave the way for industrial hemps future, a crucial step involves educating farmers, government entities, and the public about the differences between hemp types and the benefits [1-40, 41-51, 174].

Hemp fibers are used to create durable and eco-friendly fabrics for clothing, upholstery, and accessories [141, 142, 149]. These textiles are known for their breathability and resistance to mold and UV rays. Hemp fiber is making a notable comeback in the fashion industry [141, 142]. Known for its eco-friendliness, hemp textiles offer durability, breathability, and resistance to mold and UV rays [141, 142]. Designers and sustainable fashion brands are increasingly incorporating hemp fabrics into their collections, promoting its appeal as an environmentally conscious choice. Hemp's fast growth and low water requirements make it an attractive alternative to resource-intensive crops like cotton [141, 142]. As the fashion industry prioritizes sustainability, hemp fiber's versatility and minimal environmental impact position it as a key material for creating stylish, eco-friendly clothing and accessories, catering to the growing demand for sustainable fashion [141, 142, 149, 166].

2. Hemp Fibres in 3D Printing

Hemp can be transformed in filament to be used for 3D printing [52, 150, 151, 152, 166]. Biodegradable, recyclable and free from toxins, it can replace petroleum-based plastics. The material has a higher impact resistance than regular PLA [52, 150, 151, 152, 166]. Bioplastic made using hemp is fully biodegradable and compostable [52, 150]. 3D printing at Makenica in Bengaluru, Karnataka, India is revolutionizing manufacturing by reducing waste, speeding up processes, and often using less energy [52, 150, 151, 152, 166]. However, achieving a completely closed-loop system with environmentally friendly filaments remains a challenge. Hemp filament, combined with biodegradable materials like **PLA (Polylactic Acid)**, offers a sustainable solution for 3D printing service in India. Makenica is a 3D Printing company based in Bangalore, India, providing high-quality 3D Printing services to businesses and individuals [52, 150, 151, 152, 166]. With a team of experts and high-end technology, Makenica aims to provide its clients with the best 3D Printing services in Bangalore, Karnataka, India [52, 150, 151, 152]. The process of making hemp filament is relatively straightforward. Typically, PLA is used as a polymer base, and hemp fibers are ground into fine particles and mixed into the PLA [52, 150, 151, 152, 166]. This hybrid material retains the biodegradable properties of PLA while adding the unique benefits of hemp. The resulting filament often has a natural texture and color, enhancing its eco-friendly appeal. [52, 150, 151, 152, 166]. Hemp filament is a promising and sustainable alternative to traditional 3D printing materials. Its eco-friendly properties, ease of use, and unique texture make it an excellent choice for various applications. As legislation continues to evolve and more companies develop hemp-based products, the potential for hemp filament in 3D printing at Makenica, Bengaluru, Karnataka, India will only grow. Whether you are a hobbyist, a professional, or an environmental enthusiast, hemp filament offers a versatile and sustainable option for your 3D printing needs [52, 150, 151, 152, 166]. Address: Makenica HQ SLA | FDM | SLS | MJF | Vaccum casting 46, 7th Main Rd, JC Industrial Estate, Yelachenahalli, Kumaraswamy Layout, Bengaluru- 560062, Karnataka State, India. Phone + (91) 96067-70777 (www.makenica.com). Another address: Makenica Unit II-ISRO Layout, 1974, 8th Main, Stage II, KS Layout, Bengaluru-560078, Karnataka, India. (support@makenica.com).

3. Industrial *Cannabis sativa* (Hemp or fibre type)

Industrial *Cannabis sativa* (hemp or fiber type) is mainly used to produce paper, ropes, food, medicines, cosmetics, hempcrete, leather, bioplastic, biochar, 3D printing [52] and textiles [1-40, 41-52, 149, 150, 166]. This wide range of applications makes hemp a unique plant that can have positive impacts in many industries [1-40, 41-51, 166]. Recently the thermal, chemical, mechanical, and morphological properties of an alkali-treated hemp fiber-reinforced PC composite that can be formed with a 3D printer for architectural applications has been reported [52, 150]. Three-dimensional (3D) printing is an additive manufacturing process that creates a physical object from a digital design [52, 150, 166]. The process works by laying down thin layers of material in the form of liquid or powdered plastic, metal or cement, and then fusing the layers together [52, 150, 166]. Hemp has been applied in filaments for 3D printing, as a harmonic steel cable net replacement, as fiber reinforcement for automotive composite parts, and for the production of carbon nanosheets as a replacement for graphene in supercapacitors [134, 150, 166]. However, the utilization of hemp has not been fully developed globally due to the knowledge gap in its cultivation and processing and insufficient data across its life cycle [134, 166]. In addition, there has been a shortage of hemp production, a lack of process technology development, market competition with alternative crops, and regulatory risks [134, 166]. This underutilization presents opportunities for innovation and industrialization to create a sustainable and resilient agriculture system for hemp [134].

While hemp is gaining momentum as a versatile and sustainable resource, it remains a niche market facing challenges, primarily due to governmental restrictions on cultivation and harvesting. The limited knowledge in hemp cultivation and processing, especially when compared to more established fibers like flax, poses obstacles to its widespread development [1-40, 41-51]. The versatility of hemp extends beyond textiles, with potential applications in food, cattle raising, cosmetics, and construction. Within the textile industry, hemp fibers emerge as a promising solution, offering rapid growth and favorable physical properties to address existing gaps [1-40, 41-51]. The market is driven by the growing demand for industrial hemp (fiber type) from application industries, such as the food & beverage, personal care, and animal care industries, across the globe [1-40, 41-51]. Growing awareness regarding the dietary advantages of hempseed and hempseed oil, along with rising demand from the cosmetics and personal care industries will augment the market growth [1-40, 41-51]. Increasing production of soaps, shampoos, bath gels, hand and body lotions, UV skin protectors, massage oils, and a range of other hemp-based products is expected to have a positive impact on the market growth [1-40, 41-51]. Numerous health benefits and potential therapies are reported for hemp seed. Hemp seed delivers a desirable ratio of **Omega-6 to Omega-3 PUFA**, which can improve cardiovascular health, reduce osteoporosis symptoms, and diminish eczema conditions [1-40, 41-51]. Hemp seed protein is well-suited for human and animal consumption, consisting mainly of high-quality, easily digestible proteins edestin, and albumin, which are abundant

with essential amino acids [1-40, 41-51]. Industrial Hemp (fiber type) fabric is strong, hypo-allergic, and naturally resistant to UV light, mold, and mildew, which represents an added advantage over other fabrics [1-40, 41-49-51]. In addition, it can be blended with cotton or linen, which adds stretch and strength to the fabric [1-40, 51]. As a fiber crop, hemp provides a high yield; it produces 250% more fiber than cotton and 600% more fiber than flax, from the same acreage [1-40, 41-49-51]. Due to the fast-growing, dense canopy, Industrial Hemp (fiber type) is a natural weed suppressor and could be grown without herbicides ([1-40, 41-49-51]. Hemp also suppresses levels of fungi and nematodes in the soil and can be grown without fungicides or pesticides [1-40, 41-49-51]. Hemp contributes to the maintenance of soil quality by its anchored roots, which prevent soil erosion and nutrient leaching, may extract nutrients from deeper soil layers, and are effective for phytoremediation by absorbing heavy metal contaminants from the soil and storing them within the plant [1-40, 41-49-51, 166].

Industrial Hemp (*Cannabis sativa* Linn.) is a high-yielding annual crop farmed for its stalk fiber and oil-producing seeds. This specialized crop is currently experiencing a revival in production [1-40, 41-49-51, 166]. Hemp fiber contains pectin, hemicellulose and lignin with superior strength, while hemp seed oil contains unsaturated triglycerides with well-established nutritional and physiological properties. Another important fact is that industrial hemp production can, at least in some instances, compete with some existing cropping systems on a profitability basis [1-41-49-51-118]. 1) Hemp production can provide environmental and agronomic benefits when incorporated into some existing cropping systems. 2) Hemp can compete with many current inputs in industrial production, at least at current prices. Thus, even in United states that do not allow marijuana consumption and production, it is unlikely that commercial hemp production would be confused for marijuana, or vice versa [1-41-49-51]. While the plants look similar if not managed, it is different parts of the plants that have value to industrial users as opposed to recreational users [1-40]. Thus, they would not look similar when being cultivated for their specific end uses [1-41-49-51]. It has been estimated that, globally, hemp and hemp by-products can be found in more than 25,000 products that span nine sub-markets: agriculture, textiles, automotive, furniture, food, personal care, construction, paper, and even recycling [1-41-49-51-118, 166].

Hemp seed (*Cannabis sativa* L.) contain large amounts of nutrients, e.g. protein, dietary fibre, minerals, and unsaturated fatty acids, which make them a good fortifying component in food production [1-41, 149]. Hemp seeds are a rich source of nutrients. They contain about 35% oil, 25% of protein, 28% of total dietary fiber (TDF) an 5.6% of minerals [1-41-51]. Hemp protein consists mainly of a storage protein edestin (11S globulin), which accounts for 60–80% of the total protein in this raw material [1-21]. Albumin (2S) constitutes the rest of the protein fraction. Hemp seed protein is highly digestible, ranging from 84–86% for whole seeds to 83–92% for seed meal [1-40]. The main use of hemp seed processing is oil production [1-51]. Oil from hemp seeds can be a very valuable component of the diet due to its high content of unsaturated fatty acids and an appropriate omega-6 to omega-3 ratio (3:1) [1-40-51]. A by-product of hemp oil production, i.e. hemp oil cake, due to high content of protein (33.5%), dietary fibre (42.6%) and minerals (7.2%) can also be used to improve the nutritional value of foods [1-41-51]. Hemp cake is usually grounded, which makes it a highly versatile raw material used, among others, in the cereal industry [1-41-51-118].

Mariz et al., (2024) [41] are of the opinion that at the physiological level, the hemp stalk could reach between heights of 1.5 m and 5 m and have a diameter of 5 to 15 mm; this leads to a yield of fibers around 25% to 40% of the total weight of the plant [1-41-49]. Therefore, ~75% of the stalk is hurds, having many applications, but also hemp pulp for textile applications [1-41-49-51]. Additionally, and in physiological terms, hemp roots have a well developed system, reaching depths of 1 m and producing natural and organic channels, allowing the access of air, water, and the release of gases [41-49]. Thus, this network of roots allows the use of hemp as an agent for the phytoremediation of damaged soils, also making hemp an excellent candidate as a rotation plant by farmers [1-41-51]. The latter is already in use, where, in China, farmers use hemp as a rotation plant with crops like soybeans, tobacco, wheat, and corn [41-51]. Furthermore, hemp is an annual plant, which, along with its root system, has a sophisticated complex of leaves and is one of the fastest growing plants in existence [41-51]. This fact permits hemp to absorb close to 10 tons of CO_2 per hectare from the atmosphere during a single cycle of production, thus improving air quality and having a positive impact on the environment [1-41-51]. Consequently, hemp could be seen as a crop that could help achieve the goals set by the EU Climate Pact and European textile strategies to help fight climate change, such as the reduction of greenhouse gas emissions, promotion of a circular economy, natural resource management, and substitution of fossil fuel products [1-41-51]. Mariz et al., (2024) [41] reported that in terms of agriculture, hemp grows best in sandy loam-type soils with good water retention, a balanced soil in nutrients, and at temperatures between 16 and 27 ^{o}C [41-51]. This means that, to obtain high-quality fiber, good land and sufficient water must be used, contrary to the idea that, for hemp growth, minimal input is necessary when a high-quality fiber is wanted [41-51].

4. Textile Industries

Mariz et al., (2024) [41] are of the opinion that the textile industry stands as one of the largest global industrial sectors, having a market value of around 1 trillion USD [29, 41-51-118]. However, it is also recognized as one of the most polluting industries, contributing to issues such as water pollution, greenhouse gas emissions, and land occupation [29, 41-51-118]. The textile and clothing industry is one of the most polluting industries in the world [10-50]. Industrial hemp fiber is economically viable and has the potential to be a more environmentally friendly alternative material than cotton within the textile industry [29, 41-118]. Currently, one of the highest produced natural fibers is cotton, which requires intensive use of water and chemicals (i.e., pesticides and fertilizers) [29, 41-118-145]. Hemp fibres have several promising features. Specifically, they are set apart from other fibres by their aseptic properties, high absorbency, protection against UV radiation, and no allergenic effect [29, 41-118]. Nowadays, the fashion and textile market is dominated by the use of polyester (around 54%) and cotton (with a market share of 22%) [29, 41-51-118-145]. Conventional synthetic fibers, including polyester, are produced using substantial amounts of non-renewable resources and are not biodegradable [29, 41-118]. Similarly, the production of cotton, despite being a natural fibre, involves the intensive use of water, fertilizers, pesticides, and other chemicals, causing significant environmental damage to the soil and to groundwater usage [41-49-118-145]. Considering the imperative to reduce carbon emissions, focusing on environmental sustainability and develop strategies for durable, reusable, and recyclable textiles, there has been a renewed interest in the research and development of new alternative natural fibres [29, 41-118]. Among these alternatives, industrial hemp (*Cannabis sativa* L.) emerges as a key fibre in supporting the textile industry's journey towards sustainability [29, 41-118]. Currently, hemp has a market share of textile fibres of 0.3 % [41-49-118-140].

The Hemp Fabric Market size was valued at USD 16.94 Bn. in 2024 and the total Global Paper Products revenue is expected to grow at a CAGR of 32.37% from 2025 to 2032, reaching nearly USD 159.70 Bn by 2032 [143]. The hemp fabric market is witnessing significant growth driven by various factors such as increasing consumer awareness of sustainability, favorable regulatory reforms, and expanding applications across industries in North America [143]. The region is experiencing a resurgence in hemp cultivation, supported by the legalization of industrial hemp production in several states and the Farm Bill of 2024 in the United States [143]. This has led to a rise in the availability of domestically sourced hemp fiber and fabric, reducing dependency on imports and boosting the local textile industry [143]. Asia Pacific is a key region in the global hemp fabric market, characterized by a robust textile industry, high agricultural productivity, and a growing emphasis on sustainability [143]. Countries like China, India, and Australia have a long history of hemp cultivation and textile production, providing a strong foundation for the development of the hemp fabric market in the region [143]. In recent years, Asia Pacific has emerged as a major hub for hemp fabric production and exports, driven by factors such as favourable climatic conditions, abundant raw material availability, and a skilled workforce [143].

Hemp has gained significant attraction across various industries, particularly in apparel and technical textiles, owing to their unique properties and sustainability benefits [29, 41-49-118-135]. In the realm of fashion, hemp fibres are embraced for their breathability, which helps regulate temperature and ensures enduring comfort [29, 41-49-118-145]. Their exceptional durability and longevity make hemp clothing a preferred choice for consumers seeking both quality and a reduced environmental impact [29, 41-118]. Additionally, the inherent antibacterial properties of hemp fibres make them ideal for active wear and undergarments, promoting hygiene and odor control [29, 41-49-118]. Moreover, hemp's versatility allows it to be seamlessly blended with other materials, facilitating a broad spectrum of styles ranging from casual wear to formal attire [29, 41-49-118-145]. In the domain of technical textiles, hemp fibers are utilized in various applications such as automotive interiors, geotextiles for erosion control, and construction materials such as hempcrete [1-29, 41-49-118, 166]. Their notable attributes, including strength, resistance to UV radiation, and biodegradability, make them suitable for a wide array of industrial uses, spanning from sports equipment to industrial filters [1- 41-49-118-148]. As research and development efforts continue to explore advanced processing techniques and innovations, the potential applications of hemp fibres in these industries are expected to expand further [29, 41-49-118]. This ongoing exploration reinforces hemp's position as a sustainable and adaptable material poised to play a crucial role in shaping the future of apparel and technical textiles [29, 41-118]. In terms of environmental impact, hemp cultivation shows promise, surpassing cotton in positive contributions by around 70% [29, 41]. However, the slower development of hemp cultivation compared to flax results in lower yields and environmental scores [29, 41-49-118]. Continued developments and data collection in this area could unveil the true environmental impact of hemp, offering insights into potential changes in the coming years [29, 41-49-118]. **Mariz et al., (2024)** [41] are of the opinion that despite the challenges, the evident sustainability and attractive characteristics of hemp create a growing probability of its increased cultivation and utilization in various industries, particularly in the realm of textile fibres [29, 41-49-118-145].

Hemp has been the mostly blended with cotton and synthetic fibres due to barriers in the industrial process of the production of full hemp-based textiles [29, 41-49-118-140, 166]. Due to the substantial lack of innovation in the industrialization of hemp fibre production, opportunities for improvements in the different stages in the production process exist [10-50]. On the other hand, cotton has been industrialized for many years, which makes it the leading natural fibre but also limiting the likelihood of process improvement [29, 41-49-118]. The demand for product quality for both fibres requires a high operational production to ensure profitability [29, 41-49-118]. Cotton has mass economies of scale, enabling its high productivity rate [29, 41-49-118]. The requirement for a high input of hemp stalks to produce fibre has led to the investment of high straw input processing lines to allow for economies of scale [29, 41-49-118]. Currently, hemp fibre extraction has long processing lines related to a high investment cost, with low mass flows and with well-known operational problems [29, 41-49-118].

China controls over one-third of the hemp market globally and within that market, the largest share goes to hemp textile production [29, 41-49-118-145]. China has been producing hemp clothing for literally thousands of years, so this really comes as no surprise. For years, China has harvested 70% of the hemp grown in the entire world, followed by Canada, and then the US [29, 41-49-118-145]. The government temporarily banned the plant in 1985, so the modern hemp industry in China dates back to 2010. Just in that decade, China has become the **largest producer** of hemp worldwide [29, 41-49-118-145]. Hemp production and demand for hemp apparel are rising. The global hemp fibre market will likely grow from $5.76 billion to $23.57 billion between 2022 and 2030 [29, 41-49-118-145]. Compared to virgin cotton, hemp fibre's market size is still very small, but it is an ideal sustainable fibre to blend with cotton. This is because hemp is versatile and strong. As much as 60% of women wear and 75% of mens wear apparel products contain cotton, so hemp has a lot of potential. Hemp can be cottonized mechanically or chemically [29, 41-49-118-145]. Mechanically cottonized hemp results in a fabric that is more coarse than chemically processed hemp [29, 41-49-118-145]. However, better processing techniques are making mechanically cottonized hemp fibres ever finer and softer. Mechanically cottonised hemp's properties are similar to linen. It has a coarse texture that softens over time with washing. It wrinkles easily [29, 41-49-118-145].

Hemp cloth was used as early as the 5th millennium BC [139]. The fibre was one of the most widely used textile fibres until the mid-19th century. In 1850, about 75% of the world's textiles were made from hemp. In the 20th century, the use of hemp as a textile went down as the popularity of cotton and synthetic fibres grew [139]. Many countries outlawed the growing of hemp due to its association with cannabis. Global production of hemp fibre fell after 1965: from 450,000 tonnes to 100,000 tonnes in the 1990s [139]. By this time, hemp apparel was only sold in specialist hemp clothing stores. China, Canada, USA and France produce the most hemp, with estimated total areas used for hemp growing of 66,700 (2019), 36,900 (2019), 28,500 (2020) and 17,000 (2020) hectares, respectively. China and France focus on the production of hemp fibre. In the USA and Canada [139]. hemp is mostly grown for medicinal use. In the EU, **France** is the largest producer of hemp. In 2022, it grew more than 60% of EU hemp, followed by Germany (17%) and the Netherlands (5%) [139]. Other important EU-producers are Italy, Austria, Lithuania and Poland. Europe is one of the most interesting markets for sustainable apparel. There is a lot of awareness about sustainability amongst consumers, retailers, brands, governments and non-governmental organisations (NGOs) [139]. The European fashion industry is scaling up its use of more sustainable materials, and an increasing number of brands are starting to include hemp fibres into their collections, particularly in hemp/organic cotton blends for denim and T-shirts [139]. **France** is the leader of the **European hemp industry**, both in terms of growing and processing. Half of all processing facilities in Europe are located in France, and the country has 6 hemp cooperatives that focus on processing [139]. Most hemp producers are under contract with these cooperatives. France's Marmara Hemp is the first hemp fibre to be certified as fully traceable, sustainable, Cradle to Cradle (Platinum level) and with a Life Cycle Assessment performed by a certified body [139].

5. Indian Hemp Textile Industry

The **Indian textile industry** is one of the largest and most dynamic sectors in the world. With its rich cultural heritage and diverse production capabilities, India is poised to become a global textile leader by 2025 [135-138-147]. India is the second-largest textile producer in the world, with more than 3400 textile mills and an installed capacity of more than 50 million spindles and 842,000 rotors. As India move into the future, several key trends and innovations are shaping the trajectory of the industry [135-138-147]. Increasing Global Demand for Textiles, India is positioned as a leading supplier of textiles globally. By 2025, the industry is expected to see significant growth in exports, driven by increasing demand in key markets such as the United States, Europe, and the Middle East [135-138-147]. India's textile exports are projected to reach $45 billion by 2025, up from the $38 billion mark in 2020 [135-138-147]. This growth is driven by India's competitive manufacturing costs, skilled labor force, and the push to strengthen its export-friendly policies [135-138-147]. The Indian textile industry is embracing eco-friendly manufacturing practices. Sustainable textiles, organic fibres, and eco-friendly dyes are expected to become standard by 2025 [135-138-147]. The rise of sustainable brands and an increase in consumer awareness around eco-conscious products are prompting Indian

manufacturers to adopt green technologies [135-138-147]. Moreover, India is focusing on **circular economy** principles, recycling, and waste reduction in textile production [135-138-147]. By 2025, the domestic market is expected to contribute significantly to the textile industry's growth [135-138-147]. The use of hemp, banana, and bamboo fibres in India is gaining momentum due to their low environmental impact [135-138-147]. The Indian government is playing a pivotal role in transforming the textile sector through various schemes such as the Production Linked Incentive (PLI) Scheme for Textiles and the National Textile Policy [135-138-147]. These initiatives aim to boost manufacturing, exports, and job creation. By 2025, the government plans to enhance the competitiveness of the Indian textile industry, especially in high-value-added segments like technical textiles and apparel [135-138-147]. The Indian textile industry is not just focusing on exports. Domestic demand for textiles is expected to grow at a steady pace [135-138-147]. With the growing middle class, changing fashion trends, and rising disposable incomes, the demand for both traditional and modern textiles will soar [135-138-147]. Brands like Canaveda are leading the way in producing eco-friendly textiles from hemp and other sustainable fibres [135-138-147].

Digital, and 3D textile printing are emerging as game-changers in the Indian textile industry [135-138-147]. These technologies enable faster and more customized production, reducing waste and allowing for greater design flexibility [135-138-147]. As fashion trends change quickly, digital and 3D printing will allow manufacturers to keep up with demand and produce limited-edition, high-quality textiles [135-138-147]. Textile designers in India are already using 3D printing to create intricate patterns and textures on fabric, offering consumers a unique, personalized experience [135-138-147].

Hemp clothing is breathable, durable, and sustainable [135-138-148]. For India, this means reduced water consumption and pesticide use, and pressing environmental concerns [135-138-147]. Hemp requires only a fraction of the water that cotton needs, making it an eco-friendly alternative to conventional textiles [135-138-147]. Hemp shirts, for instance, offer a softer, more sustainable option, ideal for those looking to reduce their carbon footprint [135-138-147]. Additionally, hemp fabric's durability can translate into longer-lasting clothing, which is not only beneficial for consumers but also reduces the waste created by fast fashion [135-138-147]. As the demand for eco-friendly materials grows, hemp clothing in India could lead the way for a more responsible fashion industry [135-138, 147].

With increasing awareness of climate change, the demand for eco-friendly fabrics has skyrocketed. India's textile industry, traditionally reliant on cotton, has the opportunity to diversify and adopt hemp fabric as a primary material [29, 41-118, 135-138-147]. Hemp fabric is not only strong but also biodegradable. Its minimal environmental impact makes it an attractive option for industries focused on sustainability [29, 41-118, 135-147]. India's textile manufacturers can leverage these qualities, offering products like hemp bags, hemp shirts, and hemp backpacks [29, 135-138-147]. These products appeal to a growing market of eco-conscious consumers, both domestically and internationally [135-138-147]. In addition to reducing environmental impact, expanding the hemp fabric industry in India can provide rural communities with new employment opportunities [29, 135-138-147]. **Hemp Fabric Lab** in India makes innovative textiles that are either 100 percent hemp or blend hemp with fabrics like organic cotton, Tencel, silk, and wool [29]. Hemp Fabric Lab is a brainchild of BOHECO (Bombay Hemp Company). Over the past half a decade, the interest in and demand for hemp-based products is on the rise, as may be seen with the increase in the number of women artisans and weavers in rural Himalayan villages [29]. These Himalayan villages have increased the quantity and quality of indigenous hemp handloom products, such as shawls, stoles, and accessories [29]. Every inch of hemp fabric or hemp clothing comes from beautiful remote Himalayan villages of State of Uttarakhand, India made by these hard-working women. UKHI has beautifully combined all of its hemp fabrics into one album called the **Hemp Fabric Swatch Book** [29]. There are approximately 60 Fine Hemp fabrics included in the swatch book. It mostly contains pure hemp fabrics but it also has hemp cotton blends, hemp and Lycra, and Lyocell etc. These products are beautiful organic hemp fabrics and other sustainable fabric products [29]. JCRAFTECO, Ahmadabad, Gujarat, India is another eco-friendly hemp fabrication firm with stunning fabrics with zero damage to the environment. Hemploom, Noida, Uttar Pradesh, Indian Hemp, Kerala, Suvetah, 100% hemp fabric, Radhe Krishna Cotweaving, Pure Hemp Fabrics, Hemp House shop, Himachal Pradesh, and Hemp Fortex are few hemp fabric manufactures in India.

Himalayan Hemp, Kangra, Himachal Pradesh, India began with an aim to make World's 1st reusable, compostable, super-absorbent and rash-resistant hemp sanitary pads and with the help of various government grants, They are in the process of launching their sanitary pads. In line with the menstrual hygiene, they are also working parallely on other products such as hempcrete blocks, architectural design services, consultancy services, and textiles research. Himalayan Hemp is a national and international award-winning social enterprise co-founded by Haneesh Katnawer and Sonam Ratubha Sodha in 2019 with an objective to preserve the indigenous varieties of cannabis and hemp plants in the Himalayan Range.

As more brands look to produce ethically, hemp could serve as a cornerstone for fair-trade initiatives across the country, further strengthening India's position as a leader in sustainable fashion [29, 135-138-147]. Another exciting facet of India's hemp revolution is in the accessories market [29, 135-138-147]. Hemp bags, known for their strength and style, are gaining popularity. With a sturdy and natural texture, hemp bags in India are a sustainable alternative to synthetic materials. Not only do they appeal to eco-conscious buyers, but their durability also makes them perfect for everyday use [29, 135-138-147].

Hemp's rapid growth cycle means it can be harvested multiple times a year, creating an almost endless supply of raw material [29, 135-138-147]. This renewability is a significant advantage over traditional materials used for bags and backpacks. Hemp bags and accessories like hemp backpacks can support India's environmental goals by reducing reliance on plastic and synthetic materials [29, 135-138-147]. As the demand for these sustainable products grows, Indian artisans and manufacturers have an incredible opportunity to showcase their craftsmanship [29, 135-138-147]. These hemp-based products, crafted by local artisans, could potentially reach global markets, establishing India as a hub for eco-friendly fashion accessories [29, 135-138-147]. India's large agricultural sector can benefit immensely from hemp cultivation. Hemp plants require minimal pesticides, grow quickly, and can thrive in diverse climates. This makes hemp an ideal crop for farmers looking to transition to more sustainable agricultural practices [29, 135-138-147]. With proper government support, hemp cultivation could become a lucrative industry in India, offering economic benefits while reducing the environmental impact of traditional crops [29, 135-138-147]. By investing in hemp cultivation, India can generate new employment opportunities for rural communities. The hemp industry requires skilled labor for growing, harvesting, processing, and manufacturing, creating a range of jobs from farming to textile production. This job creation can empower rural communities and promote economic development in regions where employment opportunities are limited [29, 135-138-147]. Furthermore, because hemp can be grown on marginal lands that are otherwise unfit for agriculture, farmers can earn income from areas previously unused. Hemp's low-maintenance growth cycle makes it accessible for small-scale farmers, who can reap the rewards of this environmentally friendly crop [29, 135-138-147].

The Indian textile industry, one of the largest in the world, is embracing the benefits of hemp fabric [29, 135-138-147]. Hemp is naturally resistant to bacteria and UV rays, making it ideal for climates where durability and comfort are essential [29, 135-138-147]. India's historical connection to hemp dates back thousands of years, with the material playing a vital role in local economies and artisanal crafts [29, 135-138-147]. Hemp's durability, versatility, and minimal water requirements make it an ideal candidate for sustainable textile production, aligning with global trends toward eco-friendly materials [29, 135-138-147]. India's textile industry, one of the largest and most significant globally, contributes approximately 7% to industrial output, 2% to GDP, and 12% to export earnings [29, 135-138-147]. With the hemp industry poised for growth, India is positioning itself as a hub for sustainable textile innovation, with prominent figures like **Shripat Jagirdar** of Weaving Vibes and **Shridhar Jagirdar** of Karishma Exports backing the vision [29, 135-138-147]. As of now February 2025, India does not have nationwide legalization for industrial hemp cultivation. However, some states and provinces have made strides toward allowing industrial hemp farming under specific regulations. The primary hemp-producing states in India are Himachal Pradesh and Uttarakhand [29, 135-138-147].

As the world looks for sustainable solutions, hemp has emerged as a promising alternative across industries [29, 135-138-147]. From fashion to agriculture, hemp's versatility is transforming the way we create eco-friendly products. India, with its vast natural resources and growing awareness of sustainability, has the potential to lead the global hemp revolution. With a rich history of hemp use and a large pool of skilled artisans, India is uniquely positioned to redefine the hemp industry and make a significant global impact [29, 135-138-147].

India is expected to be a major player not only in textiles but also in the emerging markets of smart and technical textiles [29, 135-138-147]. Sustainability will remain a key focus, and companies that embrace eco-friendly practices will lead the way in the global market [29, 135-138-147]. However, the industry must continue to innovate, improve infrastructure, and address environmental concerns to fully realize its potential [29, 135-138-147]. As India continues to scale its textile industry, there is no doubt that it will remain at the forefront of textile manufacturing, exporting high-quality products to the world and catering to an ever-growing domestic market. The next few years will be transformative for the industry, making India a central hub for textile innovation and sustainable production [29, 135-138-147].

India's domestic market for hemp-based products, including textiles, is estimated to reach ₹3,000 crore by 2027, driven by a compound annual growth rate (CAGR) of 23% [29, 135-138-147]. Globally, hemp exports from India are poised to contribute ₹500 crore annually, with further growth anticipated as international demand for sustainable textiles surges. Hemp's contribution to the GDP of the textile sector is expected to rise significantly, aligning with the government's

target of achieving a $250 billion textile industry by 2030 [29, 135-138-147]. Currently it is believed that hemp fibers can not only revolutionize textiles but also benefit farmers by providing them with a sustainable crop that offers higher economic returns than Indian traditional agriculture. A policy shift that supports hemp farming and processing will create a massive positive impact, from the farm to the factor [29, 135-138-147].

India has the potential to lead the global hemp revolution, there are challenges to overcome [29, 135-138-147]. Legal restrictions and social stigma associated with hemp (often confused with its psychoactive relative, marijuana) can hinder its widespread acceptance. However, as more research highlights the environmental and economic benefits of hemp, the stigma is gradually fading. The government has a crucial role in helping the hemp industry flourish. The NDPS Act currently restricts the cultivation of hemp with THC levels above 0.3%, limiting the scope of its use [29, 135-138-147]. By reforming these policies and clarifying regulations, India can encourage the growth of the hemp industry while addressing concerns related to psychoactive compounds. Government support for research and development can also encourage innovation, enabling Indian manufacturers to create high-quality hemp products that compete internationally [29, 135-138-147]. Tax incentives, subsidies, and grants for hemp farmers could further accelerate the industry's growth, making it a significant contributor to India's economy [29, 135-138-147]. India's rich tradition of artisanal craftsmanship, combined with the sustainable properties of hemp, can establish a unique brand identity for Indian hemp products. By focusing on hemp clothing, hemp bags, and other accessories, India can create a line of eco-friendly products that appeal to global markets [29, 135-138-147]. For the Indian hemp industry to succeed globally, marketing will play a crucial role [29, 135-138-147]. Educating consumers about the benefits of hemp—its low carbon footprint, durability, and renewability—can help build a loyal customer base [29, 135-138-147]. Collaborating with international fashion brands focused on sustainability could further promote India as a leader in eco-friendly textiles [29, 135-138-147]. Indian brands could also use this opportunity to highlight the ethical and fair-trade aspects of their products. By promoting hemp products as both sustainable and ethically produced, India can attract eco-conscious consumers worldwide [29, 135-138-147].

India's journey to becoming a global leader in the hemp industry is not only achievable but could have lasting positive impacts on the environment and the economy [29, 135-138-147]. By embracing hemp fabric, hemp bags, and other hemp-based products, India can significantly reduce its carbon footprint and provide sustainable alternatives for consumers. With growing awareness and a supportive policy framework, India's hemp industry could play a vital role in global sustainability efforts [29, 135-138-147]. Through careful cultivation, strategic branding, and innovative product development, India has the opportunity to redefine the world's approach to eco-friendly products and set an example in environmental responsibility [29, 135-138-147]. As the demand for sustainable products rises, India can position itself at the forefront of the global hemp revolution, championing a greener, more sustainable future [29, 135-138-147].

The Indian hemp **clothing market** is a niche segment of the country's textile and fashion industry [29, 135-147]. Hemp is a natural and sustainable fiber obtained from the cannabis plant. The market's growth is driven by factors such as the growing awareness of sustainable and eco-friendly textiles [29, 135-147]. Hemp clothing is valued for its durability, breathability, and biodegradability, making it a preferred choice for conscious consumers. The growing trend of sustainable fashion and the adoption of eco-friendly materials in the apparel industry influence the demand for hemp clothing in India [29, 135-147]. However, regulatory restrictions and misconceptions related to hemp may pose challenges for market growth. The India hemp clothing market is driven by several factors [29, 135-147]. Firstly, the increasing demand for eco-friendly and sustainable textiles drives market growth. Hemp fibers, derived from the cannabis plant, are favored for their strength, breathability, and minimal environmental impact. Secondly, the trend of conscious consumerism and ethical fashion further boosts the demand for hemp clothing in India [29, 135-147]. Moreover, the growth of the fashion and apparel industry in the country adds to the market`s development, as designers and brands incorporate hemp fabrics in their collections. [29, 135-147].

The Indian hemp clothing market faces challenges related to regulatory issues, public perception, and sourcing of hemp fibres [29, 135-147]. Overcoming social stigmas and ensuring a stable supply of high-quality hemp fibres are key challenges for this market [29, 135-147]. The India hemp clothing market faced challenges during the Covid-19 pandemic. With restrictions on retail and reduced consumer spending on non-essential items, the fashion industry, including hemp clothing, experienced a slowdown [29, 135-147]. However, the market also saw opportunities as consumers increasingly sought sustainable and eco-friendly fashion choices. The pandemic emphasized the importance of conscious consumerism and ethical fashion, leading to a renewed interest in hemp clothing as a natural and environmentally friendly alternative [29, 135-147]. Online platforms and e-commerce channels played a crucial role in sustaining the hemp clothing market during lockdowns [29, 135-147]. The India hemp clothing market is catered to by key players, including Hemp Foundation, Hemp Fabric Lab, BOHECO, and Jungmaven [29, 135-147]. These companies are known for their production of hemp clothing and textiles, offering sustainable and eco-friendly alternatives in the

fashion industry [29, 135-147]. Their focus on hemp advocacy, ethical practices, and innovative designs has established them as key players in the hemp clothing market in India [29, 135-147].

Hemp is projected to reach $43.75 billion by 2030, driven by legalization and textile innovations. India's demand for organic alternatives accelerates hemp growth. Texventures, a leader in hemp textiles, partners with Kingdom Holdings, supplies 500 tons of yarn annually, and plans to double by 2026. It expands globally with B2B and B2C offerings. Hemp is projected to generate approximately $43.75 billion by 2030, with a compound annual growth rate (CAGR) of 33 per cent from 2022 to 2030 [29, 135-147]. The rise in the legalization of hemp cultivation, coupled with innovations in the clothing industry spearheaded by manufacturers and research institutions, are key factors driving the market growth. In India, the preference for organic alternatives in clothing and food is further accelerating the demand for hemp fibres, yarns, and fabrics. As the second-largest industry in India, textiles hold immense potential to boost hemp adoption [29, 135-147]. As consumers shift towards hemp-based garments, awareness of the diverse applications and benefits of hemp is expected to spread rapidly. Known for its strength and resilience, hemp fabric has become a preferred option for individuals seeking durable, long-lasting apparel. Its breathability and absorbency make it suitable for year-round use—keeping the wearer cool in summer while providing insulation during colder months. Additionally, hemp fabric's natural resistance to mould, antimicrobial properties, UV protection, and vibrant colour depth make it an attractive choice for modern consumers [29, 135-147].

Texventures, A Leader in Hemp Textiles was Founded in 2015, is a leading enterprise focused on sourcing and marketing fibres, yarns, and fabrics, both domestically and internationally [29, 135-147]. Since its inception, the company has developed a deep understanding of market dynamics and effective marketing strategies to promote natural fibres within the Indian market [29, 135-147]. Texventures centres its approach around three key pillars: innovation, marketing, and supply [29, 135-147]. The company actively educates the Indian market through various channels, including testimonials, digital ads, print media, and participation in textile exhibitions [29, 135-147]. A partnership with Hong Kong-based Kingdom Holdings, one of the largest global producers of 100 per cent hemp yarn, with an annual capacity of 4,000 tons, has allowed Texventures to secure a stable supply and meet growing demand [29, 135-147]. Texventures has established itself as a one-stop shop for all hemp textile requirements in India, providing a reliable supply of high-quality hemp yarns [29, 135-147]. In addition to maintaining a steady inventory, the company is actively engaged in market development by working closely with weavers, processing facilities, and garment manufacturers to educate them on the benefits of hemp and the techniques required to produce high-quality end products [29, 135-147]. "With cotton and polyester dominating India's textile industry, it is challenging to raise awareness about hemp's advantages and promote a shift towards slow, sustainable fashion [29, 135-147]. The company spent much of 2017 refining its production processes to deliver premium sustainable textiles to the market. Currently, Texventures supplies 500 tons of hemp yarn annually in India, with plans to double this output by 2026 [29, 135-147]. The company's fabrics division, under Mehta Fabrics and Yarns LLP, is already supplying over 200 SKUs of hemp fabrics to major hemp apparel brands in India, SMEs, and individual designers [29, 135-147]. Texventures maintains an inventory of up to 150 tons of linen and hemp yarns in India, distinguishing itself as a leader in the linen textile market [29, 135-147]. Texventures' hemp fabric range features a wide variety of weaves and designs, catering to the needs of every customer [29, 135-147]. By keeping these fabrics in stock, the company is able to meet the needs of both start-ups and designers without imposing minimum order requirements, facilitating aggressive market expansion [29, 135-147].

6. Colombian Hemp Industry

The hemp industry in Colombia has experienced resurgence in recent years, driven by a growing interest in sustainable products and the reactivation of the agricultural economy [154-165]. Hemp, scientifically known as Industrial *Cannabis sativa* L., is a versatile plant that can be used for the production of fibres, seeds, oils and other derivatives, making it a valuable resource for various industries, including textiles, 3D printing construction, food hempcrete, and biochar [1-41, 154-165].

Hemp cultivation in Colombia has been favored by suitable climatic conditions in several regions of the country, such as Valle del Cauca, the Caribbean Coast, and Antioquia [154-165]. These areas offer a convenient climate and fertile soils, allowing for optimal plant growth. In addition, Colombian legislation has begun to adapt to facilitate the cultivation and processing of hemp, which has opened up new opportunities for farmers and the industry [154-165]. In this context, hemp has positioned itself as a profitable alternative for economic reactivation, especially after the COVID-19 pandemic, which severely affected many productive sectors [154-159-165].

One of the main products derived from hemp is fiber, which is used in the manufacture of textiles, paper, and composite materials [1-154-165]. Hemp fiber is known for its strength and durability, making it ideal for applications in the

construction and textile industries [1-154-160]. For example, the use of hemp fibers in construction materials has been shown to improve the mechanical and thermal properties of products, contributing to sustainability and energy efficiency [1-41, 154-160]. Furthermore, the production of paper from hemp has been the subject of study, highlighting its potential to replace traditional raw materials such as wood pulp [1-154-165].

In the food field, hemp seeds are rich in protein and essential fatty acids, making them a valuable ingredient for the production of healthy foods [154-165]. Hemp milk, for example, has gained popularity as an alternative to traditional plant-based milks, due to its nutritional profile and low content of THC, the psychoactive compound in cannabis [1-154-165]. In addition, the hemp industry is also exploring the use of its by-products for the production of biofuels and bioplastics , which could contribute to environmental sustainability [1-154-165].

The hemp production process in Colombia faces several challenges, including the need for adequate infrastructure for processing and the lack of technical training in the management of hemp crops [154-165]. However, the growing demand for sustainable products and investment in research and development are driving innovation in this sector [154-165]. Collaboration between government, academia, and the private sector will be essential to overcome these obstacles and maximize the potential of hemp in Colombia [154-165].

Colombia has historically stood out for the production of natural fibres in Latin America, along with Brazil, Peru and Mexico, they are the largest producing countries in the region [154-165]. Textile companies achieved operating income of $ 14.34 billion pesos ($3.5 million dollars) in 2022, after the pandemic, a contribution to the GDP of 9.4% despite the low accessibility of local raw materials [154-165]. In this same year, Peru, Mexico and Brazil had textile industrial GDP of 8%, 2.9% and 20% respectively, which showed us that it is an important sector for the Colombia [154-165]. Although in Colombia there is great diversity and there are more of 100 types of fibers, such as Cestillo, Fique, Machipalo , Tripeperro , Cucharo , Chusco, Chusquín , Chusque, Guasca de Plátano, Mimbre among others, Only 20 of them are allowed to be worked with, and the Ministry of Environment and Sustainable Development regulates them [154-165]. Colombian B2B Marketplace which restricts the use of certain plant fibres to ensure the sustainable management of wild flora and non-timber forest products [154-165]. These restrictions seek to protect ecosystems and ensure that the exploitation of natural resources does not compromise their survival or negatively affect Colombian forests [154-165].

In Colombia, cotton production represents between 60% and 80% of natural fiber production [154-165]. This is why there is no real dynamic market for cotton products made from fibres other than cotton for the textile-fashion industry [154-165]. The closest thing that is detected is the market for artisanal and industrial fique fabric, which has a share of 20% to 30% of national fibre production with companies in all regions of the country, (Ministry of Agriculture and Rural Development, 2021) [154-165]. Since 2018, research has been initiated into the production of paper and textiles with pineapple and banana, promoted by the Government of Colombia through the Ministry of Science and Technology [154-165]. Therefore, to find a solution to the agricultural waste of more than 150 tons of pineapple per year produced in the Santander region [154-165]. Hence from here, the economic need arises and the industrial sector begins to produce technological alternatives for the cottonization processes [154-165]. Natural fibers share the characteristic of being composed of cellulose, hemicellulose and lignin [154-165]. In all cases the same thing is sought, the reduction of the lignin level to almost zero (like cotton) and taking into account the compatibility of mechanical properties such as tensile strength, bending strength and modulus of elasticity [154-165].

In Colombia, hemp can be produced, using the legislation of Decree 811 of 2021, which regulates the use of Cannabis and the Cannabis plant [154-165]. However, apart from this, a Law was issued only for Hemp [154-159-165]. Law 2204 of 2022 that establishes the legal framework for the Industrial and Scientific Use of Hemp in Colombia [154-159-165]. Although to date the regulations have not been issued, with this it is known that Colombia intends to invest and promote the creation of the textile sector with hemp [154-165]. The law promotes research, encourages the integration of this industry into the national economy, offering productive and sustainable alternatives [154-159-165]. As it did in 2023 with the project 'Productive development of the cannabis and hemp industries' is the strategy of the Ministry of Commerce, Industry and Tourism and Colombia Productiva, executed in alliance with Biontropic [154-165]. All these have focused on empowering these sectors as an alternative to diversify the offer and promote productive chains in the territories [154-159-165]. Colombia Productiva is an entity dedicated to promoting business development in the country, it assigned $5,000 million pesos ($ 1.2 million dollars) for the development of prototypes of materials and new ventures in the sector, of which there were winners in the textile sector [154-159-165]. This, together with international cooperation, achieved achievements such as: trade relations with China, technology transfer with universities and hemp associations from different regions of the Asian giant, a group of leaders of the Colombian textile sector was certified in a Seminar [154-159-165]. On the application of Colombian Industrial Cannabis in the textile and clothing industry at the Wuhan Textile University, licensed companies were trained in inclusion in the financial system and in certifications for competitiveness in the international market with Icontec [154-159-165]. Furthermore, calls were opened for

research and deployment of hemp genetics throughout the Colombian territory with the National University of Colombia [154-159-165].

The cottonization process of hemp fiber in Colombia is a topic of growing interest due to the unique properties of this fiber and its potential in various industrial applications [154-159-165]. Cottonization refers to the transformation of raw fiber into a material suitable for use in the textile industry and other sectors [154-159-165]. This process involves several stages, including collection, deleafing, drying, separation of fibers and their subsequent treatment to improve their mechanical and aesthetic properties [154-159-165].

In Colombia, hemp (*Cannabis sativa* L.) has traditionally been used in the production of textiles, paper and other products [154-159-165]. However, the modernization of cultivation and processing techniques has allowed an increase in the quality and quantity of the fiber produced [1-154-159-165]. Cottonization can be carried out using different methods, among which chemical, mechanical and enzymatic cottonization stand out [154-165]. Each of these methods has advantages and disadvantages that influence the final quality of the fiber [1-154-159-165]. Chemical cottonization involves the use of chemicals to remove impurities and improve fiber properties. This method can include processes such as the breakdown of lignin and hemicellulose, resulting in a softer and more flexible fibre [1-154-159-165]. However, the use of chemicals can have a significant environmental impact, which has led to the search for more sustainable methods [154-159-165].

On the other hand, mechanical cottonization uses physical processes to separate the fibers from the hemp stalk [154-159-165]. This method may include the use of specialized machinery to break down the plant matter and extract the fibers [154-165]. Although this process is less harmful to the environment, it can result in lower fiber quality if not done properly [154-159-165]. Research has shown that the quality of mechanically extracted fiber can be comparable to that of chemical fiber, depending on the process conditions [154-159-165]. Finally, enzymatic cottonization is an emerging method that uses specific enzymes to break down lignin and cellulose in hemp fiber [154-159-165]. This method is highly efficient and can result in high-quality fiber with a lower environmental impact. However, the availability of enzymes and the cost of this process can be limiting in its large-scale implementation [154-159-165].

In Colombia, practices applied to other fibers have been used in hemp fibers, such as the researchers from the FIBO research center, Fernando Murillo Hurtado and Elman Torres Colorado , who registered Patent 20220006303 of 05-20-2022 for the design of a METHOD FOR THE PREPARATION OF ANANAS SP. FIBER THREADS, AND COTTON [154-159-165]. This patent describes a method for the production of Ananas fiber threads. sp ., and cotton comprising the steps: i) pre-mixing between 37.5 and 62.5% w/w of cotton fibers and between 37.5 and 62.5% w/w of pineapple fibers sp ., ii) mixing in a loading and opening machine, iii) stirring and agitating in the loading and opening machine, iv) carding the fibers in a carding machine so that the sliver obtained is of a suitable weight for spinning v) spinning the slivers in a spinning machine that is programmed to perform between a specific number of twists per meter, producing a single-ply yarn, with a splice thickness with a specific additional percentage and an established stretch range [154-159-165]. With the proposed method, high quality yarns are produced, to be used in the manufacture of indigo or denim type fabrics. Which they have been able to apply as a cottonization methodology in hemp fibers [154-159-165].

The state of the art regarding hemp fiber cotonization in Colombia reveals an evolving landscape [154-159-165]. The increasing demand for sustainable and eco-friendly products has driven research and development in this field. Recent studies have shown that hemp fiber has superior mechanical properties compared to other plant fibers, making it an attractive material for various industrial applications, including construction and biocomposite manufacturing [154-159-165]. Furthermore, Colombian legislation has begun to adapt to facilitate the cultivation and processing of hemp, which could open up new opportunities for farmers and the industry [154-159-165]. However, there are still challenges in terms of infrastructure and technical training that need to be addressed to maximize the potential of hemp fibre in the country [154-159-165].

Colombian Hemp Market size was valued at USD 115.2 Million in 2022 and is expected to grow at a CAGR of 20% from 2023 to 2029, reaching nearly USD 412.78 Million [133]. Colombia has become a significant player in the hemp industry due to favourable climate, fertile land, and progressive regulations [133]. The country has established a robust framework for hemp cultivation, production, and export since legalizing it with THC content of 1.0% or less [133]. Colombia's diverse microclimates and ample sunlight make it an ideal location for year-round hemp cultivation, while its low production costs enhance competitiveness [133]. Colombian hemp market has experienced consistent growth, attracting companies involved in cultivation, processing, and manufacturing of hemp-based products. CBD products, including oils, tinctures, topicals, and edibles, are in high global demand, positioning Colombia as a hub for CBD production [133]. The textile industry benefits from durable and sustainable hemp fibers, offering opportunities in both domestic and international markets [133]. Hemp seeds, rich in nutrients, are utilized in various food and beverage

products such as protein powders, snacks, and beverages. The cosmetics and personal care sector incorporates hemp-based ingredients into skincare and hair care products [133]. .

In 2016, the Colombian government permitted production and distribution of hemp for medical and scientific purposes [132]. Despite optimal growing conditions and considerable foreign investment, Colombia's hemp industry is still struggling to compete globally due to market oversaturation, overregulation, and climate challenges. Simultaneously, the Colombian market remains unfavorable to U.S. exports due to internal decisions restricting imports of hemp and cannabis products to just a small number of countries [132]. The regulatory structure of Colombia's hemp and cannabis industry limits accessibility for smaller and mid-sized producers. Hemp varieties are not yet adapted to Colombia's tropical climates, leading to suboptimal production [132]. Despite these challenges, Colombia's hemp industry continues to attract foreign capital, primarily from U.S. and Canadian investors [132]. Nearly 70 percent of cannabis companies have foreign investments, culminating in an estimated total foreign investment of $400 million [132, 133] .

However, Colombian hemp industry also faces challenges [133]. Regulatory changes can impact operations, necessitating businesses to stay updated on legal requirements [133]. Increasing global competition as more countries embrace hemp cultivation urges Colombian producers to differentiate themselves and establish a strong market presence. Developing robust infrastructure and logistics networks for cultivation, processing, and exportation is essential, requiring investments in transportation, storage facilities, and processing centers [133]. Accessing global markets requires establishing trade relationships, complying with regulations, and meeting quality standards, which may involve navigating trade barriers and forming strategic partnerships [133].

The growth of Colombia hemp industry has been fueled by various significant factors. Firstly, the favorable legal environment established in 2016 has facilitated hemp cultivation and processing, attracting both domestic and international investments [133]. Secondly, Colombia's exceptional agricultural conditions, characterized by its equatorial climate and diverse microclimates, provide consistent and year-round growth opportunities for hemp [133]. Moreover, the country benefits from ample land resources, enabling the scalability and expansion of hemp operations. The cultivation, processing, and export of hemp-derived products have created substantial economic prospects, enticing entrepreneurs, investors, and businesses and driving market growth [133]. Colombia's emphasis on research, innovation, and its strategic geographic location for exports further bolster the hemp market's growth [133]. Colombia's favourable legal environment, agricultural advantages, economic opportunities, global demand, research and innovation, and export [133]. Colombia hemp potential collectively contribute to the thriving hemp industry in the country [133].

7. Role of Hemp in Brazil

The cannabis market in Brazil in 2025 is undergoing a transformative moment, driven by regulatory advancements, increasing medicinal demand, and growing interest in industrial hemp [167-169]. Despite challenges, the opportunities are immense, with the potential to transform not only the economy but also societal perceptions of the plant [167-169]. The coming decade holds the promise of positioning Brazil as a global leader in the cannabis sector, fostering innovation, economic growth, and social progress [167-169]. In Brazil, the potential of this plant is beginning to be explored more intensively as the market develops and regulations advance [167-169]. Hemp is making inroads into the textile sector, offering natural fibers with high durability and a smaller environmental impact compared to cotton [167-169]. With the growing emphasis on sustainable fashion, Brazilian brands have the opportunity to incorporate hemp into collections aimed at consumers who prioritize environmental responsibility. Industrial hemp stands out as one of the most sustainable agricultural crops available today [167-169]. Its ability to grow in diverse soil types, with low water requirements and minimal pesticide use, makes it an ideal solution for tackling the environmental challenges of Brazilian agribusiness [167-169]. Industrial hemp is not just a promising crop for the future; it is a practical and viable solution to today's environmental and economic challenges [167-169]. By embracing hemp, Brazil can pave the way for a more sustainable and prosperous future, both locally and globally. The cannabis market in Brazil is already attracting both domestic and international investors. Franchises like Hemp Vegan are expanding their operations, creating new jobs, and stimulating the local economy [167-169].

With regulations progressing and the industry gradually growing, industrial hemp is beginning to solidify its position as a promising element in Brazil's sustainable development in 2025. Its wide range of applications, combined with environmental benefits, marks the start of a transformation that could position hemp as a strategic crop for Brazil's economic and environmental future. As companies and investors recognize hemp's value, Brazil has the opportunity to lead the global market, leveraging its favorable climate and vast agricultural lands. However, achieving this potential will require public policies to encourage cultivation, support research, and promote innovation within the production chain [167-169].

In **Puerto Rico**, the Department of Agriculture has announced that there will be at least 10,000 acres of hemp grown for commercial purposes this year [167-169]. Based on good seed, training, control, and quality soil, it will be possible to develop serious work with a small, medium, or large farmers to grow hemp [167-169]. Brazil has a long and complex history with cannabis [167-169]. For decades, the plant was exclusively associated with recreational use and trafficking [167-169]. However, significant changes have occurred since the 2010s, particularly with the regulation of medicinal products derived from cannabis [167-169]. As 2024 comes to a close, the Superior Court of Justice (STJ) has set a six-month deadline for Anvisa to regulate the importation and cultivation of hemp, expanding possibilities for the market [167-169]. In 2025, Brazil is taking significant steps towards clear regulations for industrial hemp cultivation [167-169]. These regulations encompass everything from farming to exporting derivatives such as fibers, seeds, and oils. With a favourable climate and vast agricultural land, Brazil has the potential to become one of the world's largest hemp producers [167-169]. Hemp Vegan in Brazil is redefining the cannabis market with its innovative one-stop-shop model in the country's major shopping malls [167-169]. Its initiatives, including the groundbreaking medical cannabis card pilot project and mushroom-based cosmetics line, position the company as a leader in integrating wellness, sustainability, and cutting-edge technology into Brazil's cannabis ecosystem [167-169].

8. Hemp Cottonization

Hemp requires significantly less water to grow, no insecticides, no pesticides or fertilizers of any kind, rejuvenates the soil it grows in and probably has the lowest carbon footprint among textile fibre crops [29, 41-49-118-145]. The cottonization of hemp fibres presents an appealing alternative, despite its impact on the fibre characteristics [29, 41-49-118]. Hemp has huge potential for multidirectional applications. The holistic approach to hemp from the agricultural sector, industry, consumers, circular economy and environmental perspective positions hemp as one of the most important plants within the bio-economy suitable to grow to address future perspectives and initiatives [29, 41-49-118]. It solves many problems that the fashion industry is infamous for. But despite the increasing conversation around the goodness of hemp, consumers does not come across hemp-made clothing in mainstream fashion [29, 41-49-118]. This is because hemp faces many roadblocks ranging from unclear regulations to high costs that makes it inaccessible [29, 41-49-118]. One such major challenge is non-compatibility of hemp with modern textile machinery [29, 41-49-118]. The best way to process hemp is 'cottonization' of hemp. Therefore, 'cottonization' is defined as the process of converting the hard bark of a hemp plant into a cotton like structure so that it can be used on dry spinning systems [29, 41-49-118-145]. The word 'cottonization' is very loosely used across the textile/fashion industry and many people often confuse it with boiling and or opening of fibres [29, 41-49-118-148]. But it is a more holistic process which involves modifying the properties of hemp fibre to make it 'soft' and compatible for spinning [29, 41-49-118]. Again, there are many ways to cottonize the hemp fibres which involve either one or combination of enzymatic, chemical and mechanical treatments [29, 41-49-118]. The major challenge in the 'cottonization' is to balance the process in such a manner that it makes hemp soft and spinnable without damaging the functional properties of hemp fibre [29, 41-49-118-145]. Another element in the 'cottonization' process that needs to be considered is the sustainability of the process [29, 41-49-118-145]. From the amount of water used to the nature of chemicals involved, there are many factors that can impact hems sustainability [29, 41-49-118]. The additional benefits of hemp growing are the suppression of weed growth, anti-erosion, reclamation properties and the ability to drain the soil of poisonous substances and heavy metals [29, 41-49-118]. The ability of hemp plants to kill tough weeds results from several factors such as the tall height of the hemp plants, its thick leaves, and fact that it can be densely cultivated [1-39, 41-49-118].

Hemp is one of the bast fibers grown in temperate climates that have provided many important products, such as fibers for textiles and seeds (oil), as well as pulp and paper [1-39, 41-49-118-148]. Hemp elementary fibres are on average 13–15mm long with a diameter between 15 and 20 mm. They potentially display very interesting properties for industrial applications, such as high tenacity, good tensile strength and excellent moisture resistance [29, 41-49-118]. On the other hand, one of the major characteristics of hemp fibres and of natural fibres in general, limiting large-scale high-quality industrial developments, is their non-uniformity, their wide variation in dimension and variation in quality, such as strength and fineness [29, 41-49-118].

According to the Zimniewska (2022) [48] review, the most feasible direction for the development of hemp yarn production is the adaptation of the cotton spinning system to cottonised hemp fibre features [29, 41-49-118]. This is conditioned by commonly available machines, which are usually used for cotton and cotton-like fibre processes. The quality of yarn made of cottonised hemp fibres is lower in comparison to yarn spun from long hemp fibres in terms of yarn uniformity. Hence mechanical properties which result from huge differences in fibre length [29, 41-49-118]. The cottonization of hemp and the applied cotton spinning system causes hemp to lose its inherent properties like high tensile strength, cool touch, resistance to pilling and bioactivity [29, 41-49-118]. Alternatively, textiles made of cottonized hemp can be more resistant to wrinkling [29, 41-49-118]. The productivity of the cotton spinning system is

much higher than productivity of the traditional linen spinning system but only on the condition that the cottonization of hemp fibres is conducted with high accuracy [29, 41-49-118]. In this case, there is a chance to develop the production of hemp textiles for relatively low costs in the near future [29, 41-49-118]. According to the Zimniewska (2022) [48] review, the production of the best quality hemp yarn from long fibres will be dedicated to exclusive premium clothing with high prices due to the high cost of production [29, 41-49-118].

According to the Zimniewska (2022) [48] review, significant factors provide a proof of hemp sustainability and strengthen the chance for the development of the hemp textile sector as a part of holistic hemp business [29, 41-49-118]. These include the multi-perspective environmental benefits concerning hemp cultivation, such as the absorption of CO_2 from the atmosphere, improvement of soil quality and enhancing biodiversity, helping mitigate the effects of climate change and restore healthy ecosystems, as well as the possibility of using every part of the hemp plant for different purposes and wasteless industrial hemp processes, where each by-product is a valuable raw material for many sectors of the bio-economy [29, 41-49-118].

The production of high-quality hemp yarn made with long hemp fibres is limited to premium clothing [29, 41-49-118-145]. This is because there is a lack of processing capacity for long hemp fibres and the lower productivity of the traditional hemp and linen spinning system. The cottonization of hemp generally involves either mechanical or chemical processing. The challenge is ensuring that this process limits both negative environmental impact and damage to the functional properties of hemp fibre (for example, tensile strength and resistance to pilling) [29, 41-49-118-145]. While cottonised short fibre hemp may result in lower quality yarn, it also produces textiles that are more resistant to wrinkling and can have stretch properties. Textile innovators around the world are improving the cottonisation process to achieve better quality hemp fibres and yarns at more reasonable prices [29, 41-49-118-145]. By tapping into its established cotton processing infrastructure and EU buyer network, China is in a good position to benefit from technical advances [29, 41-49-118-145].

China already dominates the hemp value chain from growing to yarn-making. In 2016, China's 13th Five-Year Plan published a target to grow hemp on 1.3 million hectares of land for the production of 2 million tons of textile fibres by 2030. The country was responsible for 83% of global hemp yarn exports in 2022 according to Trade map data. Top export destinations for China's hemp yarn are India (20% of global hemp yarn exports), Korea (13%) and Cambodia (10%) [29, 41-49-118-145]. Developing country apparel manufacturers can take advantage of China's existing fabric sourcing networks to become pioneers in the production and sale of hemp clothing to the EU [29, 41-49-118-145]. Reistor is an example of an Indian sustainable clothing brand that carries a large collection of hemp products. The brand has a significant presence in the EU market, and its hemp products are sold on e-commerce sites like Wolf & Badger, LYST and Poshmark [29, 41-49-118-145].

According to Caldwel et al., (2025) [149], a gap in research and development toward hemp production is apparent in the United States due to hemp being labelled as a Controlled Substance for nearly 50 years [149]. Farmers described challenges in finding credible and reliable information to guide their decision-making [149]. Additionally, they described high costs and lack of availability of specialized equipment for hemp production, likely also a result of the gap in infrastructure caused by the decades long ban on the crop [149]. Hemp grown for cannabinoids is very labour intensive, and farmers growing for CBD were caught off guard by the high labor requirements [149]. Finding additional labour was a barrier for them and highlighted the known agricultural labour shortages [149]. Lastly, farmers described the presence of insects and weeds within their hemp crop, and a lack of control options due to limited approved pesticides, only compounded the issue [149].

9. Advantages of Hemp Cottonization

1) Hemp is a highly sustainable crop that can grow in a variety of climates and soil types [1-29, 41-49-118]. It requires less water and can be grown without the use of pesticides or herbicides. In contrast, cotton requires a lot of water and is often heavily sprayed with pesticides and herbicides to control pests and weeds [29, 41-49-118]. It is also biodegradable, making it an eco-friendlier alternative to synthetic fibres such as polyester [29, 41-49-118]. As hemp fibre is naturally resistant to mildew, mould, and pests, it is an ideal choice for organic farming practices [29, 41-49-118]. Hemp is a carbon negative fibre because it absorbs more carbon than it produces while cultivating [29, 41-49-118].

2) Hemp fabric can be used for a variety of applications, from clothing and accessories to home textiles and upholstery [29, 41-49-118]. Hemp fabric has a unique texture and appearance that sets it apart from other natural fibres [29, 41-49-118]. It can be made into a wide range of weights and textures, from lightweight, breathable fabrics to heavy-duty

canvases [29, 41-49-118]. Due to its high absorbent property, hemp is highly used to make towels. It can be blended with other fibres such as cotton, linen and silk to create unique fabrics with a range of properties [29, 41-49-118].

3) Hemp textile fibre is hypoallergenic and has natural antimicrobial properties, making it an excellent choice for individuals with sensitive skin [29, 41-49-118]. Hemp fabric is also highly breathable, which can help to regulate body temperature and keep the wearer cool and comfortable in the Indian climate [29, 41-49-118]. Hemp fibres are known for their durability and strength, making them ideal for use in products that required high durability and resistance to wear and tear [29, 41-49-118].

4) The cultivation and processing of hemp can provide economic benefits, as India's climate is very much suitable for its cultivation [29, 41-49-118]. Now hemp farming is made legal in India since 2021 and it is commercialised all over India, then it will open a huge scope for the Indian textiles and fashion industry in domestic as well as global fashion markets [29, 41-49-118]. In addition to the fashion industry, pharmaceutical, construction etc industries too will be benefitted as the hemp plant has no wastes [29, 41-49-118]. The whole plant is useful for making different products from cosmetics and medicines to geo-textiles [29, 41-49-118]. Rural communities in India, Colombia and in other parts of world will also benefit as it will create new job opportunities and generate income for farmers, weavers and artisans [29, 41-49-118].

5) Hemp has a great cultural and historical value in India because it has been grown and used here for thousands of years [29, 41-49-118]. This cultural history can be conserved and honored by using hemp in the fashion and textile business [29, 41-49-118].

6) Cotton fibres are finer, leading to a softer feel of the garment on the skin. On the other hand, hemp fabrics become softer and more lustrous through laundering and therefore, comfortability is increased with time [29, 41-49-118]. The cotton fabric degradation occurs faster and hemp fabrics turn out to be more durable and wear-proof than cotton fabrics [29, 41-49-118]. Despite higher durability, hemp fabrics are less flexible but their tensile strength is better in comparison with cotton [29, 41-49-118]. In terms of heat resistance, hemp shows outstanding results over cotton. Additionally, hemp is superior to cotton regarding moisture absorption and dissipation [29, 41-49-118]. The stated values for hemp are almost twice as high in comparison with cotton. This absorbency rate is also beneficial for dying processes, where hemp fabrics are more capable to absorb and retain the dyes being applied [29, 41-49-118]. Furthermore, it was found that the mechanical properties of hemp/cotton blends are generally 15 to 20 % better compared to pure cotton fabrics [29, 41-49-118].

7) The use of the cotton spinning system for cottonised hemp fibres makes it possible to produce pure hemp yarn or hemp blends with other cotton-like fibres by using a ring cotton spinning frame or rotor spinning. The wool-like hemp fibres can be mixed with wool and processed on the woollen spinning system [29, 41-49-118].

8) Sustainability of hemp fibre is the main strength of the whole textile sector [29, 41-49-118]. The huge amount of non-degradable synthetic oil-based fibres such as polyester, acrylic and nylon produced every year constitutes hazards for the environment, even with some of them being able to be recycled, redistributed, refurbished, remanufactured, repaired or reconstructed for use again [29, 41-49-118]. Nevertheless, synthetic fibres eventually become non-degradable waste [29, 41-49-118].

9) The possibility to cascade the use of the plant delivering natural raw materials for production of bio-products in different sectors of the economy is attracting the increasing interest in hemp growing and processing [29, 41-49-118]. Hemp is the most suitable plant to cultivate in this time of need concerning the reduction of CO_2 emissions [29, 41-49-118]. Hemp cultivation protects agricultural areas against the loss of biodiversity, improves the productivity of the soil, removes heavy metals and can be used for soil remediation and reclamation in industrial areas [29, 41-49-118]. Additionally, 1 ha of hemp plantation absorbs approximately 10t of CO_2 from the atmosphere every year [29, 41-49-118].

10) Industrial hemp can be grown strategically three crops in a year as compared to cotton. One crop required 3402 litre of water in evaluation to 9958 L/kg of cotton fibres [29, 41-49-118]. Industrial hemp emits less carbon dioxide with less energy and carbon sequestration than cotton and polyester fibres [29, 41-49-118]. Furthermore, the industrial hemp plant offers three times more fibres than cotton in the same cultivated area [29, 41-49-118]. Industrial hemp consumes less energy to come in a position to offer fibre than cotton and polyester with the sustainable route of fibre manufacturing [29, 41-49-118].

11) The utilization of natural fibres accosts ecological issues, like bio-degradability, a renewable resource, low energy consumption, low cost, recyclability, and absorb carbon dioxide in the plant's growth period [29, 41-49-118]. The surface modification of natural fibre is further enhanced between polymer and fibre to improve thermo- composites, which leads to sustainable production and consumption [29, 41-49-118]. Industrial hemp fibre is composed of cellulose, hemicellulose, lignin, pectins, and other natural contaminations [29, 41-49-118]. These natural contaminations cause fibre stiffness and obstruct spinning. Decorticated industrial hemp fibres are enzyme processed for achieving contaminations free worthy cellulose fibres [29, 41-49-118].

12) Hemp fabric is extremely easy on the skin and softens with each wash. With time, hemp has won a splendid reputation, all thanks to the designers who have been capable of integrating style, ease, and comfort.

13) Hemp fabric is extra-ordinarily environment-friendly. The plant can produce a fully nurtured crop without fertilizers or pesticides. It is grown in dense crops that do not permit sunlight, dramatically reducing weed growth, eliminating the need for herbicides. It plays a vital role in preventing soil erosion and rendering soil fertility. This means hemp cultivation is 100% organic, significantly overcoming the environmental effects and cost of producing the clothing fabric.

14) Hemp fabric is neither too thick nor too thin. The material is flowy, comfy, and its quality of thermoregulation makes it perfectly wearable in tropical as well as cold climates.

15) There is a dire need for us to save ourselves from a bleak future. Hemp could easily be an integral part of this process of change that we need to implement over the next several years. Hemp plants are carbon negative and produce relatively more oxygen than other plants. If we all switch to Hemp fabric for garments and other purposes, we can significantly reduce the global carbon footprint.

16) Materials such as nylon and polyester are synthetic fibres and are incapable of absorbing sweat. Therefore, they lack breathability. But Hemp is a natural fabric and allows sweat or moisture to pass through the cloth easily. Moreover, due to its lightweight, it does not stick to the skin. If you prefer comfort over other features, then hemp is your best choice.

17) Many fabrics lose their essence and colour after being worn because they are not resilient to the harsh sunlight. Whereas, hemp fabric is known for its ability to block blocking ultraviolet rays. Unlike other fabrics, it does not lose its colour quickly. Even after multiple wears, the hemp fabric looks as beautiful as new.

18) Hemp is 4 four times stronger fabric than cotton. If you are looking for a durable fabric that won't wear out easily, then hemp is your knight in shining armour. It can sustain a considerable amount of damage compared to other clothing materials. When used for hemp garments, the undeniable beauty of the hemp fabric is that even after several washes, it retains its strength.

19) Hemp uses considerably less water than most plants like cotton. In comparison with cotton, the hemp plant uses just half as much water to fully grow. In today's era, where water scarcity is a growing concern, hemp is way more efficient ecologically and economically, substantially decreasing the environmental harm prompted.

20) Hemp naturally resists any harmful mildew or germs due to its antimicrobial properties. The fabric also retains moisture, and you don't have to worry about body odour.This infers that it is a go-to fabric for people with allergic or sensitive skin.

21) Another best thing about hemp fabric is that it comes out beautifully in natural colours. Although designers like dyeing them with organic colours, hemp clothes in their natural shade bring a sense of elegance and timelessness with them.

22) Hemp fabric is a holy grail for fashion innovation. Not only is it gentle to the environment, but it is easily cultivated and sustainable. The fabric can play a vital role in creating a more sustainable world, not just limited to innovative and eco-fashion solutions, but in other sectors as well. Hemp is vogue and back in the game.Hemp as a fabric is yet to be completely explored. Its versatility has immense potential to be elevated as the ideal fashion choice. It is time for us to discover and adapt to this exciting fabric. By switching to this fabric with such long-lasting benefits lets unlock the door to a sustainable and eco-friendly fashion.

10. Hemp Stem Anatomy

The stalk of a matured hemp plant is made up of several layers [1-118]. The cuticle/epidermis is the outside layer which protects the cells of the stalk against moisture evaporation and sudden temperature changes, as well as partly giving mechanical reinforcement to the stem [29, 41-49-118]. The epidermis consists of stomata (pores), through which the plant ventilates and regulates evaporation [29, 41-49-118]. The thin cortex containing chlorophyll adheres to the phloem layer with bundles of bast fibres. Xylem, pith and cambium create the large woody layer which is approximately 75% of the total stalk mass and is responsible for the transportation of the soluble organic compounds created during photosynthesis as well as water and mineral distribution from the roots to the whole plant [1-29, 41-49-118]. Xylem, which is in the middle part of the plant, consists of parenchyma and vessels, which both have transport functions, and core fibres, which give the plant rigidity and strength [1-29, 41-49-118]. Fibre bundles in the phloem occur under the skin, they support the conductive cells of the phloem and provide strength to the stalk. The glutted and bonded elementary lignocellulosic fibres are located throughout the whole length of the stalk parallel to the vertical axis. In these bundles, fibres are embedded in a pectic polysaccharidic network [29, 41-49-118]. Cell wall is composed of hemicellulose, lignin and pectin. The hydrophobic lignin creates networks and bonds other molecular networks together resulting in an increase in the cellulose–hemicellulose composite stiffness, which reflects the fibre properties [29, 41-49-118]. Cellulose, which is the most desired hemp fibre compound from a final application view of point, ensures the strength of the cell wall [20] and flexibility. Hemicellulose joins cellulose and lignin together [29, 41-49-118]. Lignin enhances the strength and stiffness of the cell wall, lowers the sorption ability of the fibre and hinders chemical, physical and microbiological degradation [29, 41-49-118]. Pectin occurs in the middle lamella between the cells of all types.

11. Hemp Fibre Botany

The hemp plant *Cannabis sativa* Linn, referring to industrial hemp, is a high-yielding annual industrial crop grown providing fibres from hemp stalk and oil from hemp seeds [1-41-49-118]. Although hemp is a niche crop, hemp production is currently undergoing a renaissance [1-40]. Hemp plants can grow to heights of up to 5 m and can develop a tap root penetrating up to 2 m into the soil [1-40]. Under optimal weather conditions, the hemp plants grow from 6 to 10 cm per day. Industrial hemp plants can stand cold and heat [1-29, 41-49-118]. They have the ability to grow under mild and cool climates, preferably having a humid atmosphere for fibre production [1-40]. The plant endures light frosts, which outlines advantages towards other crops, e.g. corn, being able to survive cold temperatures down to -8 to -10° C for a shorter time [1-40]. The fibre yield increases in rainy years during the growth phase of the hemp crop [1-40]. For an increase of the total growing time, early sowing is frequently done [1-40]. This fast growth is beneficial for the weed control, since the hemp crop is suppressing the weeds [1-40]. This is the reason why hemp is one of the only crops where no herbicides and pesticides need to be utilized in the cultivation [1-40]. They grow on almost every soil, taking into account that the preferred soil for hemp cultivation is sandy loam or clay loam having a pH of 6.0 to 7.0 [1-40]. The plants root system additionally has a positive effect for farmers, as it aerates and improves the soil structure [1-40].

The majority of above ground hemp biomass comes from the tall lignocellulosic plant stalk, which has been used for fibre for thousands of years [1-40-118]. The hemp varieties largely differ in their fibre content [1-40]. Therefore, the variant needs to be well chosen [1-40]. Often, monoecious hemp plants are used for the fibre production, as they showed an advanced uniformity in growth [1-40-118]. Monoecious hemp plants are plants, which have male and female organs on the same plant, but in different flowers [1-40-118]. On the other hand, male plants are frequently preferred for fibre use, since they grow taller, the stems are thinner, and their fibre composition is superior compared to female plants [1-40-118].

The hemp stalk has two main fibre types: long **bast fibres** and short **hurd fibres** [1-40]. The outer bast fibers surround the vascular tissue of the hemp stalk, whereas the hurd makes up the woody core [1-40]. Hemp is a **bast fiber**, which means fibre is extracted from the stalk of the plant [1-40]. Conventionally, hemp fibers have been extracted in a long fibre (50–60 cm) form, with a significant quantity of short fibres [1-40]. Hemp fiber, as lignocellulosic raw material, shows similarities to other bast fibres due to the comparable chemical composition of this fibre group [1-118]. Fibers extracted from fibrous plant stalks contain cellulose, hemicellulose, lignin, pectin, waxes, fats and ash [1-40]. The bast fibre, as a lignocellulosic material, consists of mainly cellulose, hemicellulose and lignin in its chemical composition [29, 41-49-118]. Hemp fibres, similar to other natural fibers, have several bottlenecks resulting from their nature, the most significant is the lack of homogeneity [29, 41-49-118]. The lack of repeatability of fibre properties in batches delivered from farmers year by year is an essential disadvantage, the unevenness of fibre linear density, diameter and properties creates difficulties in the detailed design of processing the fibres and the planning of the quality of hemp products [1-40]. Hemp fibres showed a high ability for moisture absorption from surrounding areas, similar to other hydrophilic

cellulosic materials [1-40]. The amount of bonded moisture by bast fibres depends on the surrounding air humidity [1-40].

Hemp fibres are found in the plants outer stem tissues, referred to as bast fibres [1-40]. This is in comparison to cotton, whose textile is found in the boll or fruit [20-40]. Bast fibres are made **of primary** and **secondary fibres** [29, 41-49-118]. Primary fibers are longer and larger compared to secondary fibres [1-40]. Secondary fibres are shorter and thinner with heavily lignified cell walls [1-40]. These characteristics make the former desirable for textile use rather than the latter [1-62]. Due to their characteristics, secondary fibres are mainly used for cordage, pulp, and recycling additive purposes [1-40]. The presence of secondary fibres decreases along the stem and increases with plant age [1-40]. As bast fibers qualities change with plant age, due to the increasing presence of secondary fibre, plant harvesting time is key to increase fibre extraction quantity [1-40]. Hemp offers robust bast fibres, which are divided in primary and secondary fibres [1-40]. The primary fibres are longer and finer, whereas the secondary fibres are shorter and coarser [29, 41-49-118]. For the textile use, only primary fibres can be processed, since the size of the secondary fibres makes it impossible to process and spin them into homogenous yarns [1-40]. These primary fibres are produced during the so-called vegetative growth phase of the plant before flowering [29, 41-49-118]. The flowering generally occurs between 70 to 90 days after sowing, the harvest of the seeds normally happens 4 to 6 weeks later [29, 41-49-118]. When cultivating fibre crops, the sowing density is higher than for seed crops, as the plants are primarily growing in height and less in width [29, 41-49-118]. This leads to a higher stem yield, even if not necessarily to a higher bast fibre yield [29, 41-49-118].

Nevertheless, the secondary fibres are valuable for other end-uses [1-40]. In general, the fibres have a length from 5 to 55 mm and their diameter varies from 16 to 40 µm [1-40]. They are highly moisture absorbent, offer a good breathability and thermal insulation [1-40]. The separation of secondary fibres from primary fibres has not been accomplished effectively during fibre decertification [1-29, 41-49-118]. However, the quality variability can be reduced with the use of biological or physiochemical processing allowing for future reliable methods for industrial processing of hemp fibre [1-40]. In general, a high dry matter yield with high primary bast fibre content and low secondary bast fibre is ideal for the extraction of fibre for textile uses [1-39, 41-49-118].

The amount of European hemp fibres used for clothing only amounts to 0.1% [29, 41-49-118]. When cultivating hemp, no waste arises, since all the parts of the plant can be used for different purposes [1-40-118]. The shivs are a by-product during the separation of the fibre from the core [1-40]. Since the shivs are highly absorbent, the biggest market for them is in the field of animal bedding, having a share of 63 % [1-40-118]. Other application areas are in the use for garden mulch (19 %) and steadily growing in the construction area (16 %), e.g. as hempcrete [1-40-118]. Another profitable market for the farmers of industrial hemp is in the field of hemp seeds and oil [1-118].

12. Chemistry of Hemp Fibre

According to the Zimniewska (2022) [48] review, fibres extracted from fibrous fibrous plant stalks contain cellulose, hemicellulose, lignin, pectin, waxes, fats and ash [29, 41-49-118]. The main macromolecular compound that occurs in bast fibres is cellulose in amounts ranging between approximately 40 and 80% of dry mass depending on the fibre type, variety and extraction method [29, 41-49-118]. Cellulose is a polysaccharide and its high chemical reactivity is reached due to three hydroxyl groups –OH, which causes a high propensity for crosslinking during chemical modification. Cellulose is hydrophilic, with a contact angle between 20 and 30 degrees and is insoluble in water and most organic solvents [35]. According to the Zimniewska (2022) [48] review, a feature of cellulose, the main component of fibre, plays a crucial role in the resulting properties of hemp fibre, determines fibre absorptivity, dyeability, ability for chemical modification as well as suitability for fibre processing. Hemicellulose is one of a number of heteropolymers (matrix polysaccharides) such as arabinoxylans, present along with cellulose in almost all terrestrial plant cell walls [29, 41-49-118]. Hemicelluloses with cellulose bonded by the cross-linking of cellulose microfibrils, represent approximately 20% of the plant biomass [29, 41-49-118]. Hemicellulose dominates the middle lamella of the plant cell and provides middle-ground support for the cellulose on the outer layers of the plant cell. Hemicellulose can also interact with lignin to provide structural tissue support of more vascular plants. In bast fibres, pectin glues microfibrils and elementary fibres together, creating bundles, complexes called technical fibres [29, 41-49-118]. The presence of pectin in technical fibres is unwanted because it creates difficulties in fibre separation and further textile processing [29, 41-49-118]. The applied process of straw retting results in the reduction of pectin content in the hemp biomass. The bast fibre, as a lignocellulosic material, consists of mainly cellulose, hemicellulose and lignin in its chemical composition [29, 41-49-118].

Lignin is made up of a large group of organic polymers formed by cross-linking phenolic precursors [29, 41-49-118]. Lignin occurs in the spaces between cellulose, hemicellulose and pectin components in the cell wall. The key role of lignin in cell walls is supporting the structure of the plant tissue: xylem tracheids, vessel elements and sclereid cells [29,

41-49-118]. Lignin ensures the transport of water and aqueous nutrients throughout the plant stalk [29, 41-49-118]. The polysaccharides present in cell walls of the plant have hydrophilic characteristics, the cross-linking by hydrophobic lignin makes it possible for the plant's vascular tissue to conduct water efficiently. Lignin occurring in the bast fibres causes the reduction of the fibre's ability for water absorption [29, 41-49-118]. Lignin gives stiffness to the fibres, creating some difficulties during hemp processing. Hemp fibres are characterised by a high ability for water and moisture sorption [29, 41-49-118].

13. Hemp Retting

According to the **Zimniewska** (2022) [48] review, hemp retting is the first process of fiber extraction, determines fiber quality [29, 41-51-118-131]. The retting process, is an important and necessary step to obtain fibers from stems or leaves, where the focus of this treatment is to remove the pectin holding the fibers together [41-51, 119-131]. Through the removal of pectin, the goal is fiber extraction while maintaining the fiber morphology and mechanical potential [41-51, 119-131]. In the beginning, this happens through the gradual weakening of the interactions among the fiber bundles and the surrounding material [41-51, 119-131]. Thus, the withdrawing of any non-cellulosic compounds is necessary to obtain a cellulosic-rich fiber. Nowadays, is possible to divide retting into four different categories: physical, semiphysical, chemical, and biological. In most cases, the retting process combines two or more of these categories to achieve a higher fiber quality [41-51, 119-131]. The choice of retting method depends on factors like fibre quality, processing time, and environmental impact. In recent years, researchers have been exploring new methods and refining existing ones to improve efficiency, reduce the environmental impact, and enhance fibre properties [41-51, 119-131].

Methods of hemp fibre extraction correspond to methods developed for flax fibre, including retting as a key process of fibre extraction or the mechanical extraction with the use of decortication [41-51, 119-131]. The aim of retting, regardless of the applied method, is the degradation of the parenchyma cells, as well as in the middle lamella between the fibres to remove the non-cellulosic components and to separate the cellulose fibres [41-51, 119-131]. The main idea of the process is the biological degradation of pectin and other cementing compounds such as hemicellulose and lignin that bind the bast fibres and fiber bundles to other stalk tissues and, thereby, separate fibres from non-cellulose materials [41-51, 119-131]. Scutched long fibers used for high quality textile production are further processed on a hackling machine. Short fibres created during scutching have to be carded to prepare thicker yarns for thick fabrics, for example, upholstery, and other woven applications, as well as raw materials for nonwovens and technical products. To avoid the retting process, the stalks collected from the field can be decorticated [41-51, 119-131]. This mechanical process aims to break the stem, which allows for fibre separation. However, decortication delivers low quality, inefficiently divided bundles of fibres, with a high impurity content, making the use of this raw material unsuitable for textile purposes [41-51, 119-131]. Pure decorticated fibres are used for technical purposes, such as mats, nonwoven and other [41-51, 119-131]. To obtain clear fibres with low linear density, it is necessary to conduct the degumming process following decortication to remove the pectin-bonded fibres. According to the Zimniewska (2022) [48] review, degummed decorticated hemp fibres are processed on a carding machine in order to produce cotton-like or wool-like hemp fibres in terms of their dimensions and final application. In both cases, produced fibres are carded and shortened to make them suitable for spinning yarn with the use of a cotton or woollen spinning system [41-51, 119-131].

Fibres in the bast region of the industrial hemp plant are tiny bundles of primary and secondary fibres. These agglomerated fibres are of approximately the diameter and length of cotton fibres and remain adhered at the middle lamella by pectinacious material in the form of a bundle [41-51, 119-131]. Cottonization refers to the disaggregation of these bundles of fibres into fine cotton-like fibres by removing pectic substances [41-51, 119-131]. Researchers have investigated various methods to remove these contaminations by physical, chemical, and biological methods [41-51, 119-131]. Due to the water resistance properties of the hemp fibre, it is difficult to ferment [41-51, 119-131]. Hence, the chemical method is the prime method used for most of the processing of hemp fibre. Simultaneously chemical process consumes a significant amount of water and energy, leading to environmental pollution and less sustainability [41-51, 119-131]. Bacterial-originated enzymes have a prominent role in dissolving pectin and hemicellulose from cell walls of the complex structure of industrial hemp fibre to construct apposite fibre for the subsequent textile applications8 [41-51, 119-131]. Applying enzymes to facilitate hemp degumming effectively reduces the above problems, improves hemp quality, and reduces environmental pollution [41-51, 119-131]. Decorticated industrial hemp fibres are enzyme processed for achieving contaminations-free worthy cellulose fibres9. For spinning, industrial hemp extraction needs intriguing research to make it close to other cellulosic fibres like linen [41-51, 119-131]. The coarseness and stiffness of industrial hemp fibre restrict its applications in the apparel sector10. It is also a need of the hour to identify and optimize eco-friendly processing with an economical, sustainable, and low-temperature method for extracting good fibre from the decorticated raw fibre stage without damaging fibre quality [41-51, 119-131]. Few researchers have worked on the enzymatic action on industrial hemp fibre for separating the fibre from the cell wall to enhance the fineness with lower stiffness, which is essential for converting it into spun yarn [41-51, 119-131]. According

to the study conducted by Sahi et al., (2022) [42], the optimization of material-to- liquor ratio, treatment time, temperature, and enzymatic concentration was done using Box- Behnken response surface methodology [41, 42]. The response was recorded in the form of fibre diameter, fibre crystallinity, tenacity, weight loss, and contents of hemicelluloses and lignin in industrial hemp fibre after enzyme cottonization [41, 42]. The impact of green processing of industrial hemp is investigated in terms of ecological values [41, 42-118]. Following are the few hemp retting methods, which are currently used and which have the most potential for further development and improvement in terms of a sustainable approach.

13.1. Water Retting

This is one of the oldest method of retting used in China, India, Nepal, Pakistan, Egypt, Afghanistan, Western and Eastern European countries, and Latin America [41-51, 119-131]. This traditional method of water retting is cost effective but labour intensive. According to this method, the hemp bast fibre stems were pulled and submerged in water tanks, pools or natural water reservoirs such as lakes or rivers for five to seven days where anaerobic bacteria caused the degradation of primarily pectin [41-51-118-119-131]. In addition to this, water tanks were constructed for retting purpose only where water temperature and selected microorganisms used to improve the process could be controlled. Furthermore, these retting tanks are open aerated [41-51, 119-131]. Therefore, available air initiates the retting through the development of aerobic bacteria from the Bacillus or Paenibacillus genus and then the process is continued through anaerobic bacteria (from the Clostridium genus) [41-51-119-131]. According to the Zimniewska (2022) [48] review, the Pectinolytic microorganisms developed during water retting are Bacillus spp., dominant from 10 to 40 h after the start of the process, and are succeeded by spore-forming anaerobic Clostridium spp. when oxygen concentration in water tanks becomes lower [41-51, 119-131]. The shortest water retting time (up to 4 days) for hemp retting is possible when both aerobic and anaerobic bacteria are inoculated simultaneously in retting tanks. The hemp the stems after retting were exposed to the rays of the sun to dry and bleach on the field [41-51-119-131]. According to the Zimniewska (2022) [48] review paper, sun drying is a long process dependent on weather conditions and related to land occupation. The long hemp fibres extracted from the stem with the use of water retting are characterised by high quality in terms of fineness, mechanical properties and spinnability, which make them excellent raw materials for textiles, including apparel applications [41-51-119-131]. Zimniewska (2022) [48] confirmed that the duration of the process required for adequate retting under water (1–2 weeks) is shorter than field retting, and the dependence on weather and geographical location is minimized. Moreover, process parameters such as temperature and pH levels can be maintained to reach optimal levels in artificial water bodies [41-51-119-131]. According to the Zimniewska (2022) [48] the water retting process was the most recommended retting process for high-quality hemp bast fibre production [41-51-119-131]. Water retting is still used as one of the best method in India and other countries [48]. Apart from freshwater retting, it is possible to conduct hemp water retting in the sea. Zhang [119] confirmed the possibility of retting hemp in the sea in China [119].Sea water retting of hemp caused a significant reduction in pectin and hemicellulose content compared with the raw hemp fibre resulting from the removal of non-cellulosic gummy materials [119].

13.2. Dew Retting

The dew retting is the most common method used for flax and hemp. According to the Zimniewska (2022) [48] review, there are three methods of dew retting. a) On the field in ambient environmental conditions; b) - Retting in the greenhouses under controlled ambient conditions; c) Fost retting. Dew retting on the open agricultural field is the cheapest method because it does not need the use of special equipment apart from overturning and harvesting machines [41-51-119-131]. Dew retting is a biological process, where bacteria and fungi are employed to degrade non-cellulosic components of the fibre [41-51-119-131]. The bacteria species: *Escherichia coli, Pantoea agglomerans, Pseudomonas rhizosphaerae, Rhodobacter sp., Pseudomonas fulva, Rhizobium huautlense and Massilia timonae* as well as fungal sequences related to the genera *Cladosporium* and *Cryptococcus* occur in the majority during dew retting process. *Pseudomonas* species are particularly important in the decomposition of pectin in plant fibres in both aerobic and anaerobic conditions retting [41-51-119-131]. The activity of fungi causes the degradation of pectin-rich cells, e.g., parenchyma and, consequently, easy separation and defibration of the bast fibres from the complex stem cellular structure after two weeks of retting [41-51-119-131]. Bacteria, together with fungal species, metabolise parenchyma cells between fibre bundles with pectinolytic enzymes and hemicellulase [41-51-119-131]. The conditions of the process and retting level of the stem have to be carefully monitored because the dew-retting process has an impact on the tensile properties of elementary hemp fibres (by degrading crystalline cellulose I). According to the Zimniewska (2022) [48] review, greenhouse dew retting can only be used for limited hemp cultivation addressing special targets, which required controlled process conditions ensuring precisely designed fibre properties determined by the final application [41-51-119-131]. The greenhouse retting is very expensive and not generally used in many developing countries [41-51-119-131].

However, According to the Zimniewska (2022) [48] review due to specific weather conditions, e.g., low temperatures and high humidity during autumn, typical hemp dew retting is not effective in Nordic countries [41-51-119-131]. According to the Zimniewska (2022) [48] review the drying of wet stems laid on the field in ambient conditions is a risk due to the possibility of mould formation [41-51-119-131]. Therefore, for this reason the application of an additional drying process is necessary even it is associated with high energy consumption [41-51-119-131]. Hemp harvesting in spring and frost-retting in these countries has been developed, where the fibre separation from the stem is induced by the daily changes in temperature above and below zero during the springtime [41-51-119-131]. According to the Zimniewska (2022) [48] review water freezes and melts in the plant cell structures, which leads to an enlarging movement that loosens the bast fibre from the stem. The quality of frost-retted fibres is not too high but is enough for technical application [41-51-119-131].

13.3. Enzymatic Retting

The enzymatic retting of hemp fibres is very important due to the shortening of the process duration, the possibility to control retting conditions and manage its efficiency to obtain fibres with specific properties [41-51-119-131]. Enzymes are proteins that act as biological catalysts which accelerate chemical reactions. According to the Zimniewska (2022) [48] review enzymes hydrolyze pectin and gum material in the stem causing their degradation within a short time, e.g., between 12 and 24 h, ensuring efficient fibre separation and division into small complexes [41-51-119-131]. Specific fibre properties can be achieved for different applications by varying the retting duration and type of enzymes used [41-51-119-131]. However, disadvantages of enzymatic retting are the risk of a decrease in fibre strength and the high cost of enzymes. According to the Zimniewska (2022) [48] review, the enzymatic treatment targets more effective non-cellulosic components removal, delivers hemp fibres with good mechanical properties and lower porosity, which, when applied to reinforce composite, helps to reduce the overall environmental impact of the hemp fibre composite [41-51-119-131].

One of the study by Liu et al., (2017) [120] reported that composites reinforced with fibres obtained by enzymatic retting with the use of pure pectinase showed the highest composite strength among all the tested hemp fibres [41-51-119-131]. However, fungal retting could degrade non-cellulosic components from hemp fibres at the highest selectivity [41-51-119-131]. Both methods, fungal and enzymatic retting, deliver fibres with lower porosity content in comparison to dew retting, and in the case of the use of the fibres for composite reinforcement, result in a more homogeneous composite and better fibre–matrix adhesion [41-51-119-131].

One of the study in India by Sahi et al., (2022) [42] reported the bacteria-based enzyme's cottonization of industrial hemp fibre [42, 43]. The industrial hemp fibres are enzyme processed to eliminate massive non-cellulosic portions from the fibre to enhance their fineness and softness [42, 43]. According to the study conducted by Sahi et al., (2022) [42], Box- Behnken response surface methodology is applied and optimized the effect of different concentrations, temperature and time by using enzymes on chemical and physical properties, like weight loss, average strength, length, chemical composition, and surface modification to simulate cotton feel touch [42, 43]. The results of the Sahi et al., (2022) [42] showed that the pectin, lignin, hemicellulose, and other impurities are removed under the enzyme and alkali refining processes [42]. The effect of the enzyme concentration, treatment time, and treatment temperature is found significant on weight loss, fibre diameter, crystallinity, cellulose, hemicelluloses content, and tenacity [42, 43]. The effluent load of the enzyme process by measuring COD is also found less than that of the alkali processing for industrial hemp fibre. Industrial hemp fibre can be a perfect model of the sustainability of fibre from the plant's inception into the entire life cycle, leading to the biodegradable product reducing less effluent load in an environment [42, 43].

The study conducted by Sahi et al., (2022) [42] confirmed that the decorticated industrial hemp fibre is inappropriate for converting to yarn, fabric, and composites and can be processed by enzyme treatment [42]. The enzyme retting process can successfully replace the traditional Indian water retting process of hemp. The study conducted by Sahi et al., (2022) [42] also reported that **1)** The processing of industrial hemp by the enzyme can be done in the harvesting field at atmospheric pressure. **2)** The maximum weight loss of industrial hemp fibre is 21.24% after significantly eliminating hemicellulose and other impurities from the fibre [42]. The minimum weight loss is found 12.60%. **3)** The optimal tenacity of fibre is achieved value 21.15 g/tex and elongation at 11% [42]. **4)** The crystallinity of fibres is increased after the enzymatic treatment [42]. Higher temperature and time lead to higher crystallinity [42]. **5)**The enzymatically retted and treated industrial hemp fibre shows the highest softness due to a significant reduction in fibre diameter [42]. **6)** The COD chemical oxygen demand value in case of enzyme treatment is 3500 mg/L as compared to that is caustic soda treatment (9768 mg/L), which is much lesser for the sustainable enzymatic treatment [42]. **7)** The ideal fibre properties for cottonization can be achieved by using optimum value of enzyme, time, and temperature, keeping M:L ratio 1.10 [42].

13.4. Chemical Retting

Chemical processes used for hemp retting ensures a significant shortening of the retting period and lower costs in comparison to enzymatic processes but often yield more coarse fibres [41-51-119-131]. Chemical retting is commonly used for flax stems with complex agents and detergents buffered to a high pH with alkali. For chemical treatment addressing retting, the following agents are the most often used: EDTA, diethylene-tri-amine-penta-acetic acid, oxalic acid, tetrasodium pyrophosphate and sodium tri-polyphosphate; the alkalis commonly employed are NaOH, KOH or Na_2CO_3; sodium dodecyl sulphate is widely used as a detergent [41-51-119-131]. However, chemical retting is the use of toxic chemicals which are harmful the environment and water pollution. According to the Zimniewska (2022) [48] review paper, there is an urgent need to protect the natural environment, forcing pursuance to avoid or reduce chemical use, causing lower interest in bast fibre chemical retting [41-51-119-131]. The pro-green approach requires looking for processes characterised by low energy consumption and no chemical use [41-51-119-131].

13.5. Physical Retting: Steam Retting

Steam explosion (SE) is a process in which the lignocellulosic biomass is treated with hot steam (180 to 240° C) under pressure (1 to 3.5 MPa) and then proceeds from decompression to atmospheric pressure [41-51-119-131]. This process causes a breaking off of the fibre's rigid structure, changing the biomass into a fibrous dispersed solid [41-51-119-131]. Processing using an alkali treatment and steam explosion technique can be also preceded by the preparation of fibre, e.g., cutting into uniform size of approximately 2 mm lengths, which allows steam explosion and chemicals to penetrate deeper into the inner layers of the fibres [41-51-119-131]. SE combined with chemical modifications of hemp fibres effectively removes impurities, pectin, hemicelluloses, lignin and waxes resulting in the decrease of the fibre diameter. The effectiveness of the processes depend on the treatment conditions, parameters and composition [41-51-119-131].

13.6. Osmotic Degumming

According to the Zimniewska (2022) [48] review, osmotic degumming of bast fibres is a method used for fibre extraction based on natural physical phenomenon such as water diffusion, osmosis and osmotic pressure. Konczewicz et al (2013) [99] reported that during the water flow through the stem mass, water diffuses into the stem causing it to swell, resulting in increasing hydrostatic pressure within the stem and the epidermis in the longitudinal view is broken; however, there is no shortening the fibres [41-51-119-131]. The pectin becomes diluted and dissolved along with other substances present in the phloem in the flowing water [41-51-119-131]. Konczewicz et al (2013) [99] reported that osmotic degumming used for bast fibre extraction can deliver well-cleaned, high quality, soft, long fibres with bright colour without odour typical for water-retted fibres [41-51-119-131].

13.7. Hemp fibers

Hemp fibers also have inherent mechanical, acoustic, thermal, and physical properties. Industrial hemp is a genetically modified form of *C. sativa*(L) plant containing low THC (Δ-9 Tetrahydrocannabinol) value of below 0.3%. In one of the study by Sahi et al., (2021), an attempt has been made to cottonization of Indian industrial hemp fiber. The fibers were given an alkali treatment for the removal of non-cellulosic content [1-41-51-119-131]. Three different levels of concentration, time and temperature were selected for the treatments on the Box-Behnken response surface design principle [41-51-119-131]. The effect of alkali treatment on mechanical properties viz; length, strength, and weight loss and physical properties viz; diameter, surface were analyzed. This process has eliminated the Indian traditional tedious water retting and time-consuming process used on Hemp fibers. The resultant fiber obtained from the proposed process is textile grade quality and spinnable by the cotton dry spinning system [41-51-119-131]. The effect of alkali treatment on the mechanical and physical properties was found significant [41-51-119-131].

13.8. Steam explosion (SE)

Sauvageon et al., (2017) [44] reported that steam explosion (SE) is currently one of the most valuable pretreatment technologies for cellulosic bio-ethanol production [44]. After impregnation, biomass is treated with hot steam (around 200°C) under pressure (around 1.5–3 MPa) during a few minutes followed by an explosive decompression [44]. The effect of SE on biomass combines chemical hydrolysis during the stream treatment and defibration during the explosive decompression [44]. During Impregnation, hemp biomass was impregnated with a solution of sodium hydroxide (0; 4; 8 wt %) [44]. The fibers were macerated for 15 h at room temperature using a weight ratio water/biomass of 15/1 after which the biomass was filter-pressed (6.8 atm¼100 psi) to remove the excess water [44]. After pressing, the fibers were transferred into a 4.8 L steam gun where about 100 g (dry basis) of biomass was cooked at temperatures ranging from 190°C to 210°C for 1, 3 or 5 min by the addition of steam in a pressure resistant reactor [44]. After the cooking period, a pneumatic valve is opened and the vapor phase exits the reactor through a nozzle entraining, as well the fibers [44]. A washing step was necessary after the steam treatment to remove the residual NaOH in the fibers. Therefore, biomass

was washed with 1.5 L of water at 12°C, without stirring, for 15 min and then filter-pressed (6.8 atm¼100 psi) [44]. This washing step was repeated three times after which the fibers were dried in an oven at 104°C for 24 h [44]. After drying the fibers were conditioned at 20°C±2°C and 65%±4% relative humidity (RH) [44]. A typical carding machine with a main cylinder and three pairs of worker and stripper rollers was used, whereby a cylindrical surface of the cylinder is provided with a specific clothing for natural fibers. Fine hemp fibers (cottonized hemp) were processed using steam explosion [44]. The quantification of the defibration rate was performed by image processing. Based on this method by Sauvageon et al., (2017) [44], the hemp defibration was optimized using a response surface methodology based on three-variable central composite design for the production of elementary fibers with low variability. Optimal parameters for the steam processes were as follows: time= 4.1 min; temperature= 191°C [44].Biomass was impregnated with a solution of NaOH (8%) before treatment, leading to a defibration rate of 91.2%, which is producing =50% fibers with length <3 mm, in good agreement with the experimental data [44]. Damaged fibers originating from the conjugated effect of steam explosion and alkali hydrolysis were also observed [44].

In addition to traditional retting methods, recent innovations have introduced new approaches that leverage computer analysis and metabolic studies of microbiota found in natural environments, such as water and dew retting [41-51-119-131]. These methodologies employ metagenomics, which involves investigating the genetic material present in environmental samples using molecular tools like 16S rRNA gene amplification [41-51-119-131]. By applying the techniques to processes like hemp or flax retting, researchers aim to identify superior bacterial strains with enhanced enzyme activity crucial for selective retting, such as pectate lyase, pectinase, hemicellulose and ligninase, while minimizing cellulase activity [41-51-119-131]. This focus on specific enzyme activities preserves the natural structure and properties of the fibers, resulting in higher-quality fibers suitable for high-end textile applications [41-51-119-131]. Metagenomics holds promise in addressing various challenges associated with different retting methods. It can help achieve more consistent results lacking in dew retting, reduce water pollution in water retting, lower the costs associated with enzyme use in enzymatic retting, and eliminate harsh chemical usage in chemical retting [41-51-119-131]. Moreover, metagenomics-based approaches offer scalability advantages, as selected colonies of microorganisms in artificial tanks can achieve superior fiber quality in shorter durations compared to traditional methods, harvest after harvest 41-51-119-131].

According to the Zimniewska (2022) [48] review of literature survey, the diversity of possible methods for hemp fiber extraction that conditions the fibre chemical composition and properties gives stakeholders the opportunity to select technology that would be the most suitable for their capability and final application [41-51-119-131]. Based on the reviewed methods of fibre extraction, it can be concluded that three methods with the lowest environmental impact will be developed in the future, e.g., dew retting, water retting with a circular water system and renewable energy use as well as mechanical extraction with the use of decortication [41-51-119-131]. The first two methods ensure good quality of long fibres, the last one provides raw materials suitable for cottonisation or technical application. The use of enzymatic retting is limited due to the high price of enzymes, while chemical retting is not neutral to the environment [41-51-119-131].

The applied method of fiber extraction from the stalk determines the effectiveness of the removal of the gluing substances and dividing the technical fibres on smaller fiber complexes in pursuance of obtaining elementary fibres [41-51-119-131]. The grade of the fiber separation is reflected in the fibre dimensions and properties. Hemp fibres, similar to other natural fibres, have several bottlenecks resulting from their nature, the most significant is the lack of homogeneity [41-51-119-131]. The lack of repeatability of fibre properties in batches delivered from farmers year by year is an essential disadvantage, the unevenness of fibre linear density, diameter and properties creates difficulties in the detailed design of processing the fibres and the planning of the quality of hemp products [41-51-119-131].

Interest in hemp as a viable cellulosic fiber for clothing has increased, driven partly by its economic benefits and the importance of natural renewable materials in emerging circular economies [144]. However, the coloration and chemical finishing of lignocellulosic fibers such as hemp typically require large quantities of water and chemicals [144]. Recently one of the study by Bapat et al., (2024) [144] reported an Argon plasma pre-treatment provides a way of modulating the physical properties of hemp fibres to improve the coloration process without compromising other bulk properties such as tensile strength [144]. Such plasma treatments may contribute to alleviating the negative environmental impacts associated with liquid pretreatments, heating, or the use of auxiliary chemicals [144]. Dyeing of hemp fibres is particularly challenging due to its crystalline chemical structure [144].

13.9. Hemp fiber Extraction

Following the retting stage, a critical and common step in fiber-related applications is fiber extraction. Typically achieved through mechanical means, the primary goal is to separate the woody core and obtain individualized fibers

[41-51-119-131]. Successful fiber individualization requires the retting process to be stopped at the appropriate time, allowing the stems to dry and facilitating the contraction of fibre bundles for easy release [41-51-119-131].

The choice of fibre extraction method depends heavily on the desired fibre properties, in which length and fineness are the most critical. Long hemp fibres, between 50 and 70 cm long, can be obtained to be processed in flax machines and produce short fibres as a by-product [41-51-119-131]. Decortications is an extraction method that allows obtaining fibres in a more direct way and without the need for alignment of the stems to feed the machine or without the retting process [41-51-119-131]. This process tends to break the nucleus, allowing fiber separation and obtaining fibres with a low level of individualization and high level of impurities, making these fibres not suited for high-value applications such as apparel textiles but applicable in nonwovens production [41-51-119-131].

The resulting fibers of the decortications process can still suffer a process of degumming to remove pectins, making them more suitable to be processed in a carding machine, with properties similar to cotton in terms of length and fineness [41-51-119-131]. Moreover, one of these machines' greatest advantages is the high process capability with the use of hammer mills, where a single machine can reach a productivity of several tons per hour [41-51-119-131]. This next step is called scutching, which is based on the beating of blades on a disk across its length in a way that removes its impurities, as well as promoting the individualization process of fibres, making them thinner and softer. The hurds are rubbed and crushed by the rotating tambour and separated by gravity. This process demonstrates high efficiency, achieving a rate of 500 kg per meter of the working width [41-51-119-131]. After this process, there is a final step, the hackling process, where the fibers are combed with combs progressively finer to align the fibers and reduce their diameter without reducing their length. The combs are supported on two rotating belts parallel to each other with adjustable speeds [41-51-119-131]. Some authors demonstrated that, when using the process described previously with an optimized retting process, it is possible to obtain hemp fibres with a quality and mechanical properties comparable to flax fibre, for which these processes are developed [41-51-119-131].

Long fibres are usually considered the best quality of fibers when regarding flax/hemp, although specific spinning processes are required, namely wet or semi-wet spinning processes, allowing 100% hemp yarn production. Regarding the semi-wet spinning process, a pre-treatment of roving is required. In both cases, there is also the possibility of making blends with flax fibers [41-51-119-131]. In addition, through means of the cottonization of hemp fibers, is possible to use ring and rotor spinning systems, making feasible the blend of hemp fibres with other fibre types. However, normally, using these systems is not possible to obtain 100% hemp yarn [41-51-119-131]. Lastly, there is the possibility to use wool systems to produce blended hemp/wool yarns. To achieve such prowess, hemp fibers must be decorticated but also pass through a specific carding machine, which enables them to obtain wool-type hemp fibres [41-51-119-131]. Through this spinning system, it is possible to achieve yarns with 90% hemp fibers [41-51-119-131].

13.10. Disadvantages of Hemp Cottanization

1) A major disadvantage of hemp fibers towards cotton fibers is their lack of uniformity. The hemp fibers highly vary in length and diameter, which makes it more difficult to process and spin them into uniform yarns.

2) The bottle neck for the hemp textile value chain is the spinning system. The traditional linen spinning technology seems to be the most suitable for hemp yarn production for textile/clothing purposes but the system requires a very specialized machine park containing machines which have not been produced for several decades and are difficult to find on the market. Other existing spinning systems, such as cotton or wool spinning technologies, can be adapted for hemp fibres, making the production of pure hemp yarn or blended hemp with relevant natural or man-made fibres possible.

3) The linen spinning system needs hemp fibres prepared according to a determined procedure. The harvested straw must be retted with the use of one of the possible retting methods, then the dry stem has to be cut to 0.8–1 m lengths and scutched.

4) The linen spinning system should be treated as a basic well-known technology ensuring the best quality of yarn from hemp long fibres, many challenges are associated with the system. The first challenge causing serious limitation in the use of the system is difficulty to complete the technological line due to the lack of producers interested in the construction of the machines. The hackling machine is unique, it can be used only for flax/hemp long fibre processing, it is not possible to include it in other fibre spinning systems. The limited demand for the machines is determined by the niche character of the flax/hemp sector. The share of flax/hemp fibres in the world production of all types of fibre was less than 1% in 2019. It means that the development and production of new hackling machines for very niche hemp is economically unprofitable.

5) But the biggest challenge is on the other side, that have to source the hemp fiber from outside India and that adds to the cost. This is one aspect that stops most of Indian manufacturers and brands from offering a good price on hemp clothing. In order for retail to accept the hemp products, it is believed that the concept needs to get more acceptable within India and just for to create awareness or give washing guide is not enough. The Indian market still has the stigma of comparing hemp with marijuana. However, hemp is an extremely durable and versatile fabric that uses 50 per cent less water as compared to cotton. In fact, there are two sides of the coin; on one side of it, there is 'Marijuana' that has so many medicinal uses and on the other side have 'Hemp', which can use to make more than 20,000 products [1-118]. The entire hemp plant from seed to foliage can be used purposefully [1-118]. Hemp is versatile and biodegradable and this is one of the few plants whose by-products can either be eaten, sat on, written on, worn, slathered on human body, painted on a wall or squirted into a machine.

6) The cost increases as the raw materials are imported. The absence of processing infrastructure also contributes to the high price of hemp [29]. To transform hemp into useful fibres, yarns, and fabrics, specialized machinery and knowledge are needed [1-118]. However, India's existing lack of infrastructure for processing and producing hemp products can drive up production and distribution costs [29]. Additionally, the cost of hemp products increases due to the need for certifications and conformity with international standards [29]. For instance, hemp products must adhere to tight criteria for THC levels and other quality indicators in order to be exported to the EU or USA [29]. This requires additional testing and certification procedures, raising the production cost [29]. Despite the high cost of hemp in India, the use of this eco-friendly and sustainable fiber can have a transformative impact on the fashion and textile industry of the India [29].

7) There are various factors that contribute to the high cost of hemp in India compared to other cellulosic fibres [29]. One of the main factors is mass hemp cultivation is banned in India [29]. Although hemp has been grown in India for centuries, its cultivation is restricted to certain states due to legal and regulatory barriers [29]. In 2021, India has legalized hemp as food and licenses have been sanctioned for growing hemp throughout India. While it is often confused with marijuana, hemp is a distinct variety of the same plant species, *Cannabis sativa* and contains only trace amounts (0 to 0.3%) of THC (Λ9-Tetrahydrocannabinol), the psychoactive compound found in marijuana [1-40]. This causes limited supply of hemp in India, so mostly hemp-based businesses are run by importing hemp yarns, fabrics or hemp extracts from other countries like China, France, Italy, Canada and USA etc [1-40].

8) Comparing the profitability of hemp yarn production is difficult due to the diversity of methods possible to use for the same value chain, e.g., there are many retting technologies, many available combinations of technological lines and different machines providing varying levels of productivity [29-118-130]. The traditional spinning systems are characterised by low productivity, nevertheless modern technological solutions still on a laboratory scale or semi-commercial scale [29]. The cost of production depends on the type of production system applied and should be evaluated individually for each case [29].

9) The lack of production of specialized industrial machines dedicated to hemp fibres results in the high diversity of technological lines used and makes it impossible to evaluate the universal economic aspects of hemp yarn manufacturing [29-118].

10) The fact that hemp is a niche fibre means that the development of the hemp fibre sector meets many challenges, with the most significant weakness being the lack of specialized modern machines required to complete the technological line [29]. Hemp spinning is not an attractive direction for producers of machines, such as the hackling frame dedicated to the long fibre process, which guarantees obtaining the best quality hemp yarn and final product [29]. Existing traditional equipment usually used for yarn production is characterised by low productivity, which makes the process economically unviable [29].

11) Increasing profitability of hemp textile production allows for facing social challenges. Population ageing is a challenge for the European economy and society. This phenomenon is also visible in the hemp sector, where a generation gap is observed [29-118]. Employees in the European bast fibre sector are experienced workers aged 50+, as the interest of young people to work in hemp sector is very low [29-118]. It is necessary to create an education system to ensure competent farmers and staff to operate tools or machines, implement new technologies and develop the hemp industry [29-118].

12) The education system should also aim to increase social awareness in terms of the sustainability of bio-products and the effects of hemp on the environment and human life [29-118].

13) One of the most significant weaknesses in hemp production lies in the dearth of specialized modern machinery designed for comprehensive hemp processing, spanning from field to fiber to yarn. This deficiency, especially evident in hackling and spinning machines dedicated to producing high-quality long hemp fibres, can be traced back to years lost under restrictive regulations [29-118].

14) Hemp garments are generally more pricey than other alternatives. The main reason for this is that this fabric is not as mainstream as other alternatives, such as cotton.

15) Some hemp fabrics need a little extra maintenance than other options out there. Hemp fabric – especially delicate types – can shed the first time when wear it, although only if some one work up a sweat. However, any shedding of this material is actually harmless. Plus, one can always prevent shedding by hand washing new hemp garment before its first wear.

16) Additionally, while hemp might shed a little on the first wear, synthetic fabrics have been known to relieve extensive amounts of microfibers during every wash cycle. This explains the concern around microfiber pollution that harmfully affects both environmental and human health.

17) Hemp garments do tend to wrinkle – just like most natural fibers. However, since hemp clothing lasts a while and becomes more comfortable over time, the advantages still seem to outweigh this drawback. After all, one can reduce wrinkles in hemp by taking on a few practices, usually encompassing the drying process.

18) The disadvantage of hemp clothing is that, since it is natural, it does not have the color richness that synthetic materials do. One could argue that hemp fabric never looks as 'nice' as synthetic clothing, instead having an organic, natural look. So, hemp might not be for any one if one love vibrant colors. However, by providing subtle and neutral colors, one could argue that hemp fabric is excellent for accessorizing and can provide a highly sophisticated look.

14. Conclusion

The resurgence of cannabis (*Cannabis sativa* L.) has been propelled by changes in the legal framework governing its cultivation and use, increased demand for hemp-derived products, and studies recognizing the industrial and health benefits of hemp. Commonly cultivated for its strong fibers, which were used to produce textiles, ropes, and sails, hemp was a valuable commodity in many industries and everyday life. Additionally, hemp seeds were used as a food source and in traditional medicine for their nutritional and therapeutic properties. Hemp fiber contains pectin, hemicellulose and lignin with superior strength, while hemp seed oil contains unsaturated triglycerides with well-established nutritional and physiological properties. Therefore, focus on the utilization of hemp in various industries is increasing globally. Hemp fibers mainly consisting of cellulose derivatives have superior strength to be used as reinforcements in thermoplastic packaging and paper. Bast fibres have higher cellulose content and are stronger than hurd fibers which have higher lignin content and are unsuitable as composite material reinforcement. Hemp fibres and seeds have been used traditionally for many purposes, including clothing, building materials, paper, nutrients, and human and animal health. Hemp exhibits great promise as a sustainable alternative to traditional materials and crops. Its versatility, carbon sequestration capabilities, and moderate growth cycle make it an attractive option for numerous industries seeking eco-friendly solutions.

Hemp fibres have been used for millennia in the production of textiles and fabrics. Hemp fabrics are known for their durability, breathability, and resistance to UV rays. Hemp textiles are not only environmentally friendly but also offer a sustainable alternative to traditional cotton and synthetic fibres. Methods of fibre extraction include dew retting, water retting, osmotic degumming, enzymatic retting, steam explosion and mechanical decortication to decompose pectin, lignin and hemicellulose to remove them from the stem with varying efficiency. This determines further processes and proves the diversity of ways to produce yarn by employing different spinning systems such as linen spinning, cotton and wool spinning technology with or without the use of the decortication process.

However, there are several challenges associated with hemp processing as the fibre is coarse, stiff and it has comparatively poor spinnability particularly when 100% hemp is processed in ring spinning system. While India has the potential to lead the global hemp revolution, there are challenges to overcome. Legal restrictions and social stigma associated with hemp (often confused with its psychoactive relative, marijuana) can hinder its widespread acceptance. However, as more research highlights the environmental and economic benefits of hemp, the stigma is gradually fading. The lack of production of specialised industrial machines dedicated to hemp fibres results in the high diversity of technological lines used and makes it impossible to evaluate the universal economic aspects of hemp yarn manufacturing. Digital, 3D Printing and 3D textile printing are emerging as game-changers in the Indian textile industry.

These technologies enable faster and more customized production, reducing waste and allowing for greater design flexibility. Due to market oversaturation, overregulation, and climate challenges, Colombia's hemp industry still struggles to compete globally.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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